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RESPONSE OF A TURBOJET AND A PISTON-ENGINE TRANSPORT AIRPLANE TO RUNWAY ROUGHNESS

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Langley Research Center

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SUMMARY

An investigation has been conducted to determine the response characteristics of a turbojet transport airplane and a piston-engine transport airplane on runways having different roughness characteristics. Airplane normal-acceleration response increased with increasing taxi speed and was of about the same magnitude at the center of gravity of both airplanes at similar taxi speeds on the same runways. Root-mean-square normal accelerations in the pilot compartment of the turbojet airplane exceeded those at the center of gravity by from 45 to 110 percent. Pitching velocity and normal acceleration measured near the center of gravity and in the pilot compartment of the turbojet airplane during taxiing on the three runways varied in magnitude in the same order as did the relative levels of roughness indicated by power spectra of the runway profiles. For the turbojet airplane, the ratio of the airplane normal-acceleration spectra to the runway spectra did not define a unique transfer function which was independent of input amplitude and airplane speed.

INTRODUCTION

A number of studies have been made of various aspects of runway roughness because of the importance of roughness effects to the design and operation of airplanes and to the construction and maintenance of runways. Studies have been made to evaluate the roughness characteristics of existing runways from profile measurements, to determine the response of different types of aircraft to runway roughness, to correlate aircraft response with roughness characteristics, and to define acceptable levels of roughness. (See refs. 1 to 11.)

Results are presented of an investigation made to determine the response characteristics of a large turbojet transport airplane and of a small piston-engine transport airplane in relation to runway roughness. Pitching velocity and normal acceleration at the center of gravity and normal and transverse acceleration in the pilot compartment of the turbojet airplane were measured during constant-speed taxiing runs at four speeds on three runways and during a take-off and landing. Normal-acceleration response at the

center of gravity of the smaller piston-engine airplane was measured during taxiing on two of the runways. Runway roughness characteristics were obtained from elevation profiles measured along the center lines of the runways.

The results of the investigation are presented in the form of profiles and power spectra of the runways and root-mean-square values, maximum values, and power spectra of normal-acceleration response of the airplane for each run. Pitching-velocity spectra of the turbojet airplane for some of the runs are included. Transfer functions, the ratio of output center-of-gravity normal-acceleration spectra to the input runway spectra, are given for the turbojet airplane. Normal-acceleration response at the center of gravity of the turbojet airplane is compared with the response of the piston-engine airplane at similar speeds for the two runways on which both airplanes were tested.

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 12.

a_n airplane normal-acceleration increment, g units

$a_{n,max}$ maximum normal-acceleration increment, g units

a_t transverse acceleration measured in pilot compartment, g units

$a_{t,max}$ maximum transverse acceleration measured in pilot compartment, g units

f frequency, cycles per second

g acceleration due to gravity ($1g = 32.2$ ft/sec^2 = 9.8 m/sec^2)

q airplane pitching velocity, degrees per second

q_{max} maximum airplane pitching velocity, degrees per second

$|T(f)|^2$ amplitude squared of transfer function, $\left|\dfrac{\text{g units}}{\text{foot}}\right|^2, \left(\left|\dfrac{\text{g units}}{\text{meter}}\right|^2\right)$

λ wavelength, feet (meters)

σ_{a_n} root-mean-square value of airplane normal-acceleration increment, g units

σ_{a_t} root-mean-square value of transverse acceleration in pilot compartment, g units

σ_q root-mean-square value of airplane pitching velocity, degrees per second

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

$\Phi_h(f)$ power-spectral-density function of runway elevation for a specific taxi speed, square feet per cycle per second (meter^2 per cycle per second)

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

$\Phi_q(f)$ power-spectral-density function of airplane pitching velocity, (radians/second)^2 per cycle per second

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

APPARATUS AND METHODS

Description of Airplanes

Turbojet transport.- A photograph of the large turbojet-powered transport used for the investigation is shown in figure 1 and a drawing of it is shown in figure 2. For the tests, the airplane gross weight varied from approximately 155 000 pounds (mass) (70 307 kg) to 142 000 pounds (mass) (64 410 kg). The airplane was provided, maintained, and operated by the Federal Aviation Agency. Instrumentation was provided and installed by NASA.

Piston-engine transport.- A photograph of the piston-engine transport used to measure response to two of the runways is shown in figure 3 and a drawing of it is shown in figure 4. The taxi runs were made at an airplane gross weight of about 40 000 pounds (mass) (18 144 kg). The airplane was owned, operated, and instrumented by NASA.

Instrumentation

Turbojet transport.- The turbojet-powered airplane was equipped with a pitching-velocity recorder, a single-component normal-acceleration recorder, a normal- and transverse-acceleration recorder, and a 0.1-second timer. The recording instruments were mounted on two thick dural panels which were rigidly attached to the airplane structure at floor level. The single-component accelerometer and pitching-velocity recorder were located near the center of gravity of the airplane about $16\frac{1}{2}$ feet (5.0 m) ahead of the main landing gear; the other accelerometer was located in the cabin immediately behind the pilot's seat about $4\frac{1}{2}$ feet (1.4 m) ahead of the nose wheel.

The sensitivity of the pitching-velocity recorder was about 15.3 deg/sec/in. (6.02 deg/sec/cm) of film deflection. The normal accelerometers at the nose and near

the center of gravity had sensitivities of 1.81g and 0.53g per inch (0.71g and 0.21 g/cm) of film deflection and had flat frequency responses to 13 and 6 cps, respectively. The transverse accelerometer at the nose had a sensitivity of 2.02g per inch (0.8 g/cm) of film deflection and had a flat frequency response to about 13 cps.

Piston-engine transport.- The piston-engine airplane was equipped with a commercial strain-gage acceleration transmitter, an 0.1-second timer, and an oscillograph recorder. The normal-acceleration transmitter was located near the center of gravity of the airplane. The accelerometer had a sensitivity of about 5.36g per inch (2.11g/cm) of film deflection and the system had a flat frequency response to about 10 cps.

Runways

A diagram of the runways used for the investigation is shown in figure 5. Sections of the runways over which airplane-response measurements were made are indicated on the diagram. The three runways, hereinafter called runways A, B, and C, were located at two international airports. The test sections for runways A, B, and C were 4200, 5600, and 3000 feet (1280, 1707, and 914 m) long, respectively. The intersections of other runways with runways A and B are indicated in figure 5. There are no runway intersections on runway C, a newly constructed runway.

Test Procedures

For the turbojet airplane, constant-speed taxiing runs were made over the three runway test sections. One take-off was made on runway A and one landing on runway B. The pilot was instructed to avoid braking during the test portion of these runs. The taxiing runs at nearly constant speed were made in the same direction at approximately 25, 50, 80, and 130 knots. In order to enable the pilot to maintain the desired test speed, a car was used to pace the airplane at 25 and 50 knots and the airspeed indicator was used at speeds of 80 and 130 knots.

For the piston-engine airplane, constant-speed taxiing runs were made at about 46, 73, and 96 knots on runway A and at 47 and 97 knots on runway B. Taxi speed was determined from the airplane airspeed indicator.

The tracks of the nose wheels of the airplanes were along the center lines of the runways. The elevation profiles of the center lines of the test sections of the runways were surveyed at 2-foot (0.61 m) intervals with a precision surveyor's level, rod, and steel tape. The runway profiles at the time of the taxi tests are believed to have been about the same as when the surveys were made.

DATA REDUCTION

Determination of Runway Power Spectra

Power spectra of the runway profiles were computed by the method described in reference 11 from elevation measurements obtained from the surveys of the runways. Two sets of 40 power estimates were computed by using elevation profile data at 2-foot (0.61 m) and 8-foot (2.44 m) runway-station intervals to define the power spectra of the runway profiles for wavelengths from 320 to 4 feet (97.54 to 1.22 m).

Response and Speed Measurements

The normal-acceleration records for the airplanes were read at 0.05-second intervals. The data were used to obtain maximum and root-mean-square (rms) values of incremental acceleration. Spectra of incremental acceleration consisting of 41 uniformly spaced power estimates were computed over the frequency range from 0 to 10 cps by the method used in references 10 and 11.

The pitching-velocity and transverse-acceleration records for the turbojet airplane were also read at 0.05-second intervals for a landing on runway B and for a take-off and a constant speed run at 82 knots on runway A. Power spectra of pitching velocity were computed by the same procedure used for obtaining the normal-acceleration spectra. In addition, maximum values of pitching velocity were read for each run.

Taxiing speed of the turbojet airplane was determined from the recorded time required for the airplane to traverse the known lengths of runway test sections. For the piston-engine airplane, approximate ground speeds were obtained from readings of the airplane airspeed indicator corrected for wind velocities.

Transfer Function

The amplitude squared of the transfer function of the airplane $|T(f)|^2$, was determined from the relation

$$|T(f)|^2 = \frac{\Phi_{a_n}(f)}{\Phi_h(f)}$$

where $\Phi_{a_n}(f)$ is the output spectrum of the normal acceleration of the airplane and $\Phi_h(f)$ is the input spectrum of the runway roughness along the center line. This relation for the transfer function is based on the assumption that the system is linear and that the response is due to a single input. As is well known, however, the landing gears of airplanes are extremely nonlinear. Also, runway roughness constitutes not a single input but, rather, consists of three inputs through the two main gears and the nose gear.

In order to determine the extent to which these violations would nullify the practical application of the transfer functions in calculating airplane response, the present measurements were used to provide information on the consistency of the functions for different levels of roughness.

Accuracy

The runway elevation readings are estimated to be accurate within ±0.002 foot (±0.061 cm). This accuracy is sufficiently high for the errors to be of the same order of magnitude as the ordinary surface texture irregularities. Consequently, the errors are negligible insofar as the elevation profiles are involved. Although there is no precise method available for determining the effect of this reading error on the runway roughness spectra, estimates indicate (ref. 11) that the spectra are essentially unaffected by the error for wavelengths longer than about 10 feet (3.05 m) but that they may be significantly in error for shorter wavelengths. However, inasmuch as ordinary short-wavelength roughness deviations of low amplitude (excluding chuck holes and the like) make only insignificant contributions to airplane response, the indicated errors in the spectrum at the short wavelengths are thought to be unimportant.

On the basis of instrument accuracy and data-reading errors, it is estimated that maximum values of pitching velocity, normal and transverse acceleration in the pilot compartment, and normal acceleration near the center of gravity of the turbojet airplane are accurate to within ±0.1 deg/sec, ±0.015g, ±0.015g, and ±0.005g, respectively. Maximum values of normal acceleration for the piston-engine airplane are estimated to be accurate within about ±0.04g. Root-mean-square values of response are estimated to be accurate within ±0.001g and ±0.002 deg/sec for the turbojet airplane and within ±0.003g for the piston-engine airplane. These errors would have a negligible effect on the acceleration spectra.

The reliability of the transfer functions is affected by errors in both the acceleration and runway elevation readings. In the present investigation, it is thought that the effects of reading and instrument errors are secondary to other factors which affected the accuracy of the transfer functions. A general discussion on the effect of errors on the computation of transfer functions is given in reference 13.

RESULTS AND DISCUSSION

Runways

The three runways used in the investigation are shown schematically in figure 5. Runway A had been the object of a number of complaints of excessive roughness whereas runway B was regarded as a good runway and runway C was considered to be

exceptionally smooth. Profiles of the center lines of the test sections of the runways are shown in figure 6 and enlargements of a portion of the sections are shown in figure 7. A 0.3-percent grade has been removed from the profile of runway C. The profiles indicate that runway A is the roughest runway, runway B is smoother than A, and runway C is the smoothest of the three runways.

The power-spectral-density functions of the runway profiles are shown in figure 8. For comparison, the criteria suggested in reference 7 for "new construction" which gives a level not to be exceeded in runway construction is also shown in the figure. The power spectra indicate that runway A is considerably rougher than the criteria for new construction, runway B approximately meets the criteria, and runway C is considerably smoother than the criteria.

Airplane Responses

General response characteristics.- Turbojet-airplane time histories of normal acceleration at the center of gravity, normal and transverse acceleration in the pilot compartment, and pitching velocity are shown in figure 9 together with the elevation profile of the runway over which these responses were measured. The data shown are for a taxi speed of about 82 knots on runway A. Several response characteristics are evident from examination of the figure. The normal-acceleration response is characterized by low-frequency oscillations at a frequency of approximately 3/4 cps $\left(\text{sometimes at } 1\frac{1}{2} \text{ cps}\right)$ with other low-amplitude oscillations superimposed at about 4 cps, $5\frac{1}{2}$ cps, and other higher frequencies. Normal-acceleration response is approximately twice as great in the pilot compartment as at the center of gravity of the airplane. Intermittent periods of transverse acceleration with amplitudes from 0.10g to 0.25g at a frequency of about 10 cps are evident for the pilot compartment. The pitching-velocity response is characterized by oscillations at a frequency of approximately 3/4 cps.

A comparison of the airplane-response time histories with the runway profile (fig. 9) shows that in some cases a particular response peak can be associated with a particular irregularity of the runway but that, in general, such association is not readily apparent.

Root-mean-square normal acceleration for constant taxiing speeds.- Root-mean-square values of normal acceleration of the test airplanes for various taxi speeds are shown in figure 10. Over the range of test speeds, the root-mean-square normal acceleration at the center of gravity of the turbojet airplane increased with speed from about 0.05g to 0.08g on runway A, from about 0.02g to 0.04g on runway B, and from about 0.02g to 0.03g on runway C.

Acceleration response at the center of gravity of the piston-engine airplane was about the same as for the turbojet airplane at corresponding speeds for runways A and B on which both airplanes were taxied.

The root-mean-square normal accelerations at the pilot compartment of the turbojet airplane exceeded those at the center of gravity by from 45 percent to 110 percent.

Comparison of the turbojet normal accelerations shown in figure 10 indicates that the highest accelerations were measured on the runway indicated by the spectra (fig. 8) to be roughest (runway A) and that the lowest accelerations were measured on the runway indicated by the spectra to be the smoothest (runway C). Thus, the relative roughness levels as indicated by airplane acceleration responses and by roughness power spectra are in qualitative agreement.

Maximum normal accelerations for constant taxiing speeds.- The maximum positive and negative values of normal accelerations recorded for each run are shown in figure 11. Maximum values of normal acceleration at the center of gravity of the turbojet and piston-engine airplanes are seen to be of similar magnitude for comparable taxi speeds and runways. Maximum accelerations of 0.50g, 0.27g, and 0.18g were recorded in the pilot compartment as compared with -0.28g, 0.16g, and -0.10g near the center of gravity on runways A, B, and C, respectively. As with rms accelerations, the relative values of maximum accelerations are consistent with runway roughness levels shown in figure 8.

Power spectra of normal-acceleration response.- The power-spectral-density functions of normal-acceleration response for the turbojet airplane at various speeds on three runways are shown in figure 12. The data are shown in figure 12 for frequencies up to 7 cps although the accelerometer at the center of gravity has a flat response to about 6 cps with the result that there is a slight attenuation (less than 10 percent) at 7 cps. The spectra exhibit similar characteristics even though variations in detail are apparent. The amplitudes of the spectra generally increase with increasing taxi speed and runway roughness. The major response frequencies shown at approximately 3/4 cps and $1\frac{1}{2}$ cps to $1\frac{3}{4}$ cps are thought to be the pitch and vertical translation modes, respectively. Several other modes at higher frequencies are also present in the spectra. At the center of gravity (fig. 12(a)) the major response occurred at a frequency of approximately $1\frac{3}{4}$ cps at taxi speeds of about 25 knots, at somewhat lower frequencies for increased taxi speeds, and at about 3/4 cps at 130 knots. The major low-frequency response in the pilot compartment (fig. 12(b)) was at a frequency of about 3/4 cps for all the test speeds.

A comparison of the spectra of acceleration near the center of gravity with those in the pilot compartment of the turbojet airplane on runway B for two speeds is shown in figure 13. These comparisons, which are typical of those for other speeds and runways,

8

show that the spectra are consistently higher in the low-frequency range for the pilot compartment than for the center of gravity. The increased acceleration spectra for the pilot compartment results from the pitching motion of the airplane and accounts for the higher rms accelerations previously noted for the pilot compartment.

Power-spectral-density functions of normal-acceleration response near the center of gravity of the piston-engine airplane for runways A and B are shown in figure 14. Trends for the piston-engine airplane are similar to those which have been shown for the turbojet airplane. For similar taxi speeds, the spectra show greater response on runway A than on runway B and generally show an increase in response with an increase in taxi speed. The frequency of the predominant mode varied from around 1 to $1\frac{1}{2}$ cps.

A comparison of the response spectra for the two airplanes is shown in figure 15 in which the power-spectral-density functions of normal acceleration at the center of gravity of the piston-engine airplane are compared with those of the turbojet airplane for similar speeds on runways A and B. The similarities of the accelerations at the center of gravity of the two airplanes in magnitude and frequency are thought to be coincidental and these similarities do not necessarily hold for other locations in these airplanes nor apply to other transport airplanes.

Normal accelerations for turbojet airplane during take-off and landing.- Root-mean-square and maximum values of normal accelerations for the turbojet airplane for a take-off on runway A and for a landing on runway B and accelerations for the high-speed taxiing runs on these runways are given in the following table:

Run	Runway	Turbojet-airplane normal acceleration at -			
		Center of gravity		Pilot compartment	
		σ_{a_n}, g units	$a_{n,max}$, g units	σ_{a_n}, g units	$a_{n,max}$, g units
Take-off	A	0.08	-0.30	0.12	±0.49
High-speed taxi	A	0.08	-0.29	0.13	0.50
Landing	B	0.05	0.18	0.10	0.37
High-speed taxi	B	0.04	0.16	0.08	0.27

Accelerations for the landing impact and the following 2 seconds are not included in the tabulated data. Take-off accelerations were about the same and landing accelerations were slightly higher than for high-speed taxiing runs on corresponding runways.

Power spectra of normal acceleration for a take-off over the test section of runway A and a landing on runway B are compared with spectra for taxi runs at 130 knots on these runways in figure 16. Spectra for the take-off and for the 130-knot taxi run are

in general quite similar. However, spectra for the landing are flatter over the frequency range and are of greater magnitude at frequencies below 3/4 cps and above 1 cps than are the spectra for the constant-speed run.

Pitching velocity.- Maximum values of pitching velocity of the turbojet airplane for each constant-speed taxi run on the three runways are shown in figure 17. Pitching velocities are highest on runway A, which has been indicated by runway spectra to be the roughest runway, and are lowest on runway C, the smoothest runway. The values generally increase with taxiing speed except that no increase was measured at speeds higher than 82 knots on runways A and B. None of the pitching velocities exceeded 2 deg/sec during the constant-speed taxi runs and a maximum of about 1.55 deg/sec was measured during a take-off on the test section of runway A.

The power-spectral-density functions of pitching velocity for the 82-knot taxi run and take-off on runway A and the landing on runway B are shown in figure 18. The spectra indicate a predominant frequency response at about 3/4 cps for the constant-speed taxi run and somewhat lower frequencies for the take-off and landing runs. Root-mean-square values of pitching velocity for the constant-speed run, take-off, and landing were 0.71, 0.40, and 0.77 deg/sec, respectively.

Transverse acceleration.- Inasmuch as the pilot is affected by airplane responses in the transverse direction, these accelerations were also examined. Transverse-acceleration response in the pilot compartment of the turbojet airplane was generally less than 0.05g for all taxiing runs on runway C, the smoothest runway, and for the lowest taxi speed on runways A and B. However, maximum response measurements of approximately 0.25g were recorded on runways A and B during the three higher speed taxiing runs and for a take-off on runway A. More response was apparent on runway A than on runway B for a similar taxiing speed. The response time history which was shown in figure 9 for a taxiing speed of 82 knots on runway A is generally typical of that measured for other high-speed taxiing runs. Response usually was characterized by intermittent periods of moderate-amplitude high-frequency oscillations at approximately 10 cps with other lower amplitude oscillations present at various frequencies. Transverse-acceleration values for three of the test runs are given in the following table:

Run	Runway	Turbojet-airplane transverse accelerations in pilot compartment, g units	
		σ_{a_t}	$a_{t,max}$
Taxi at 82 knots	A	0.059	0.26
Take-off	A	.059	.24
Landing	B	.087	.32

Transfer Functions

Transfer functions of turbojet-airplane center-of-gravity normal accelerations for the three runways at various taxi speeds are shown in figure 19. Examination of figure 19 indicates that the functions are in fair agreement as regards the frequencies at which the predominant peak amplitudes occur. Fair agreement in amplitude is shown for runways A and B at similar speeds. However, in general, large variations in amplitude for different speeds and for similar speeds on different runways are apparent. Transfer functions determined for the pilot compartment also showed large variations with speed and with runway roughness level. Previous investigations of other aircraft have shown similar variations in transfer functions obtained by the power-spectral method.

CONCLUDING REMARKS

An investigation has been conducted to determine the response characteristics of a turbojet transport and a piston-engine transport airplane in relation to runway roughness.

The turbojet and piston-engine airplane root-mean-square (rms) normal-acceleration values at the center of gravity increased with increasing taxi speed and were of about the same magnitude for both airplanes at similar taxi speeds on the same runways. Corresponding rms accelerations in the pilot compartment of the turbojet airplane exceeded those at the center of gravity by from 45 to 110 percent. On the roughest runway maximum normal accelerations of about 0.28g and 0.50g were recorded near the center of gravity and in the pilot compartment, respectively, of the turbojet airplane.

Maximum and rms normal accelerations measured near the center of gravity and in the pilot compartment of the turbojet airplane during taxiing on the three runways varied in magnitude in the same order as relative levels of roughness indicated by power spectra of the runway profiles.

Predominant normal-acceleration response was at about 3/4 cps and $1\frac{1}{2}$ to $1\frac{3}{4}$ cps for the center of gravity and about 3/4 cps for the pilot compartment of the turbojet airplane. Other higher frequency responses were also evident. The large values of airplane response at a low frequency of only 3/4 cps points out the strong influence of long-wavelength runway deviations on airplane response at high speeds.

Transfer functions for the turbojet airplane determined from the ratio of the output airplane normal-acceleration spectra to the input runway spectra did not define a unique transfer function which is reasonably independent of input amplitude and airplane speed.

Langley Research Center,
    National Aeronautics and Space Administration,
   Langley Station, Hampton, Va., September 23, 1965.

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Figure 1.- Turbojet transport airplane.   L-62-9660
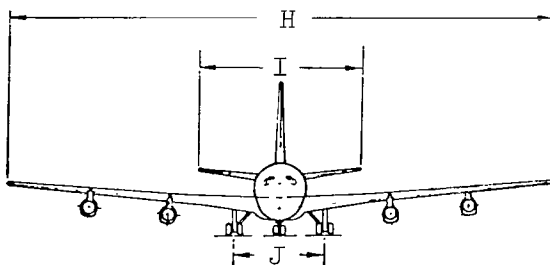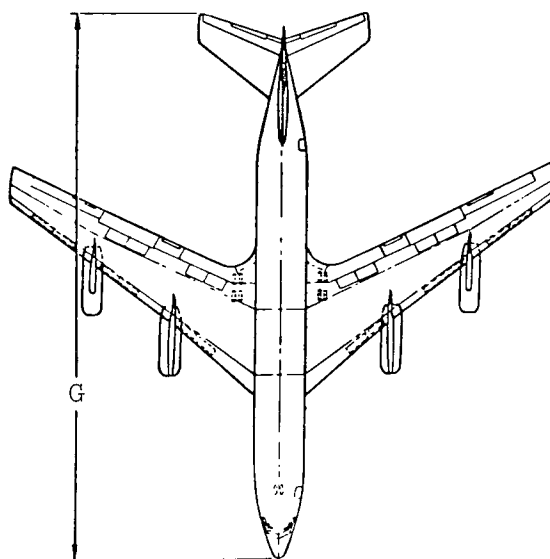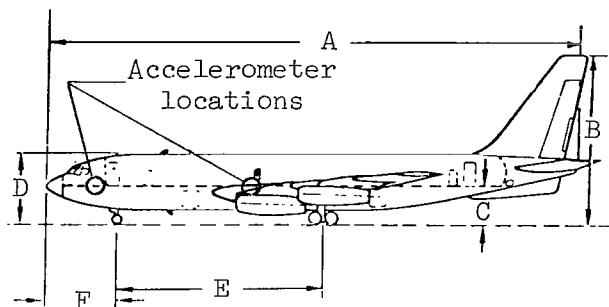
	Feet	Meters
A	130.50	39.78
B	41.17	12.55
C	9.75	2.97
D	17.75	5.41
E	50.67	15.44
F	17.42	5.31
G	136.17	41.51
H	130.83	39.88
I	43.00	13.11
J	21.92	6.68

Figure 2.- Three-view drawing of turbojet transport airplane.
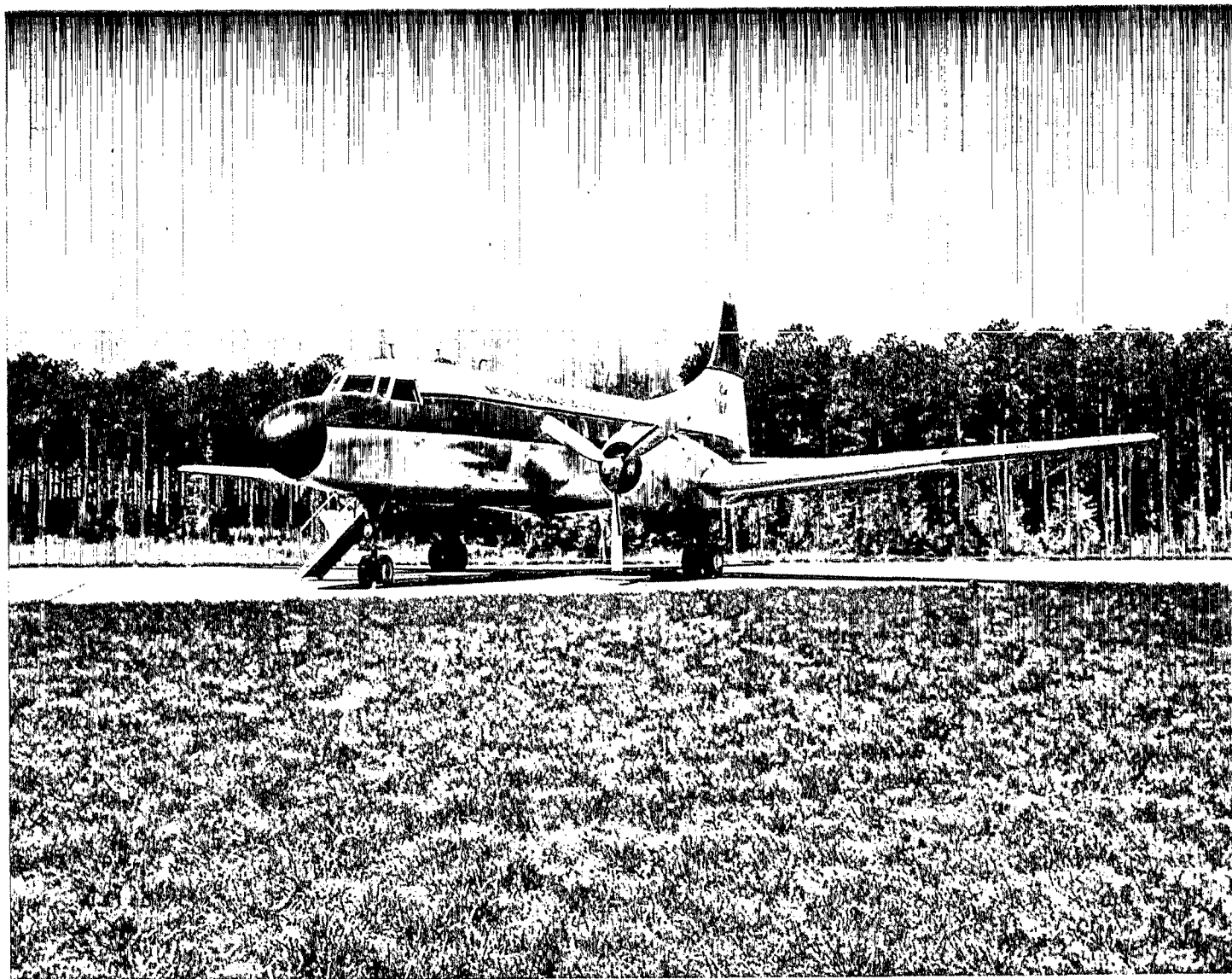
Figure 3.- Piston-engine transport airplane.

L-63-2840
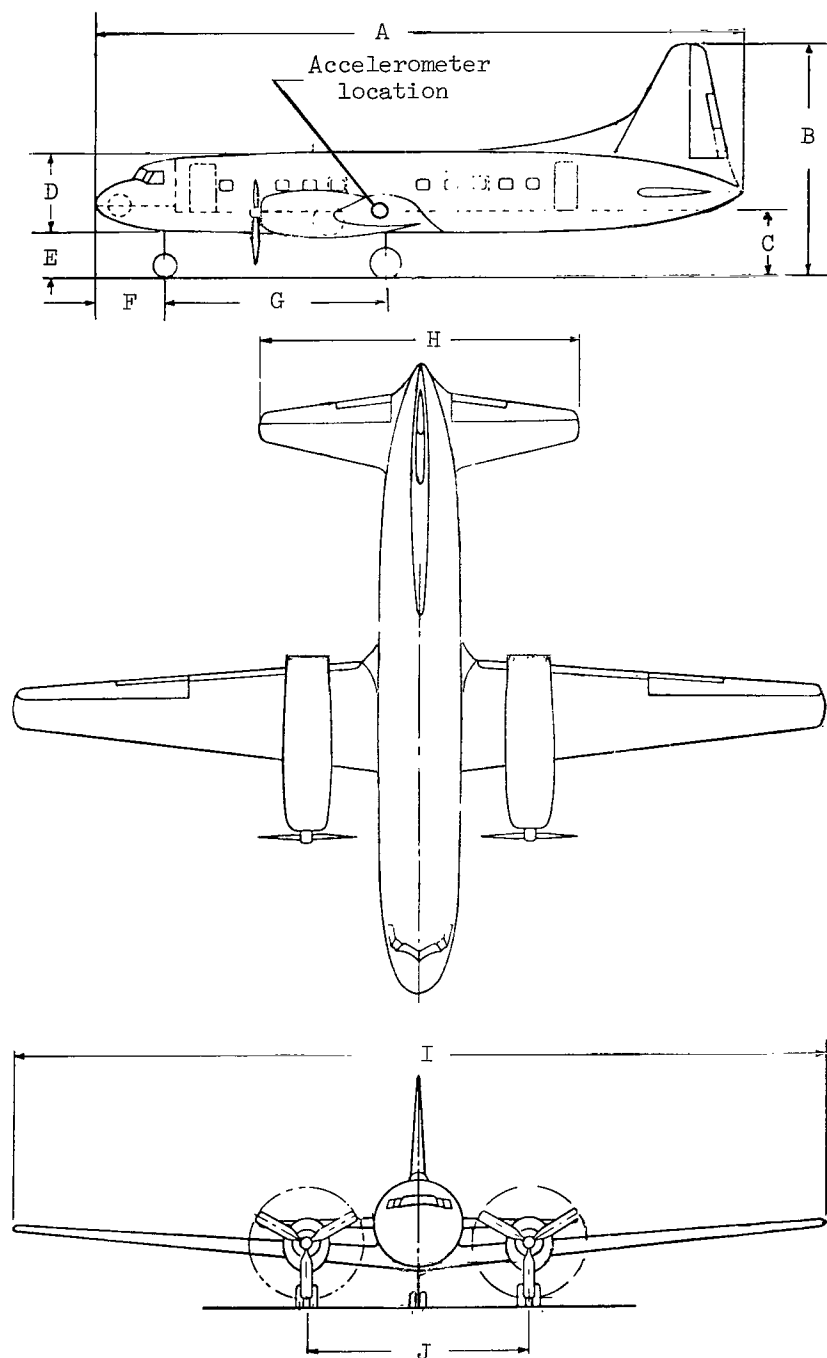
	Feet	Meters
A	74.67	22.76
B	27.25	8.31
C	7.58	2.31
D	9.42	2.87
E	5.00	1.52
F	7.92	2.41
G	24.83	7.57
H	36.46	11.11
I	91.75	27.97
J	25.00	7.62

Figure 4.- Three-view drawing of piston-engine transport airplane.
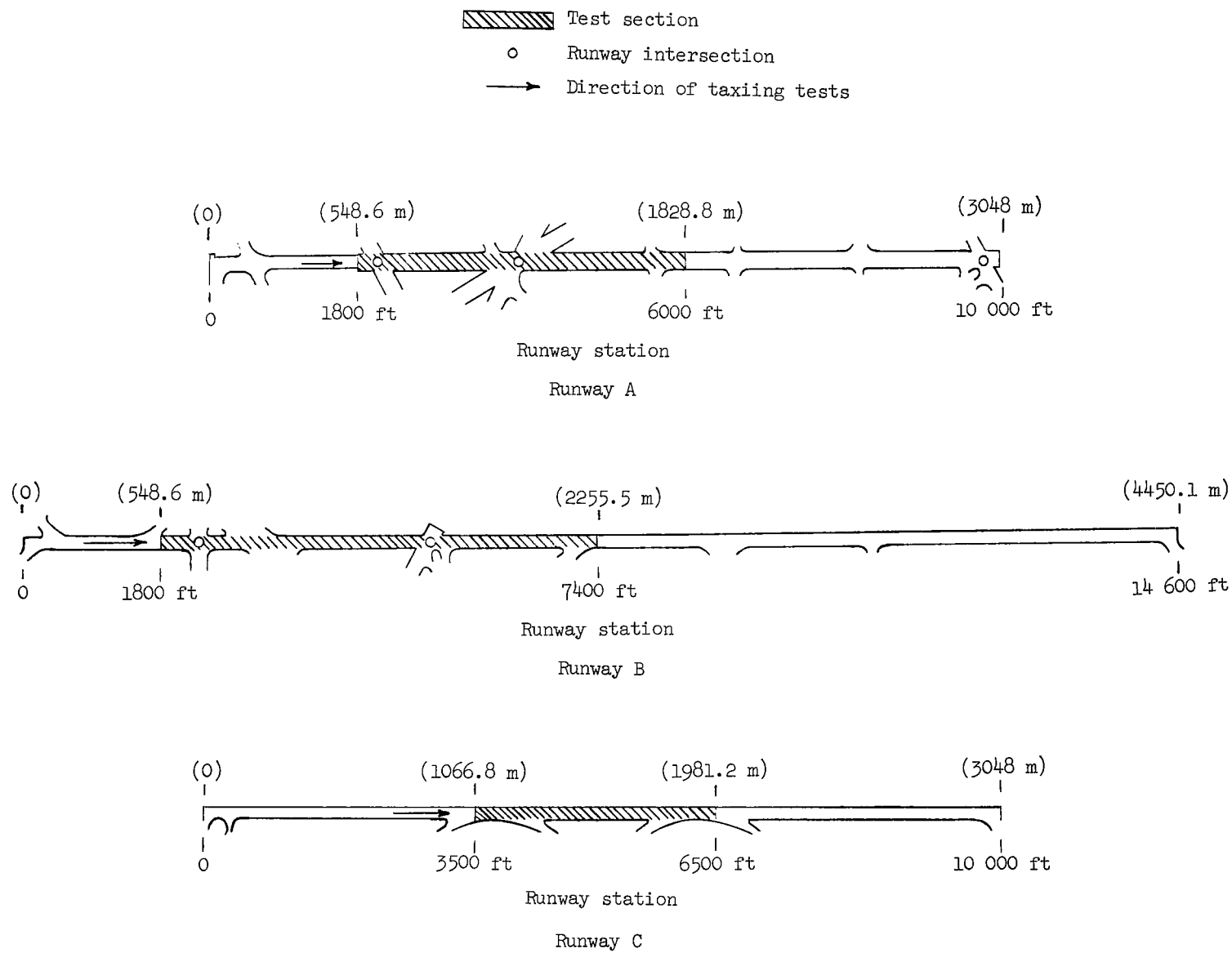
Figure 5.- Diagram of runways used for investigation.
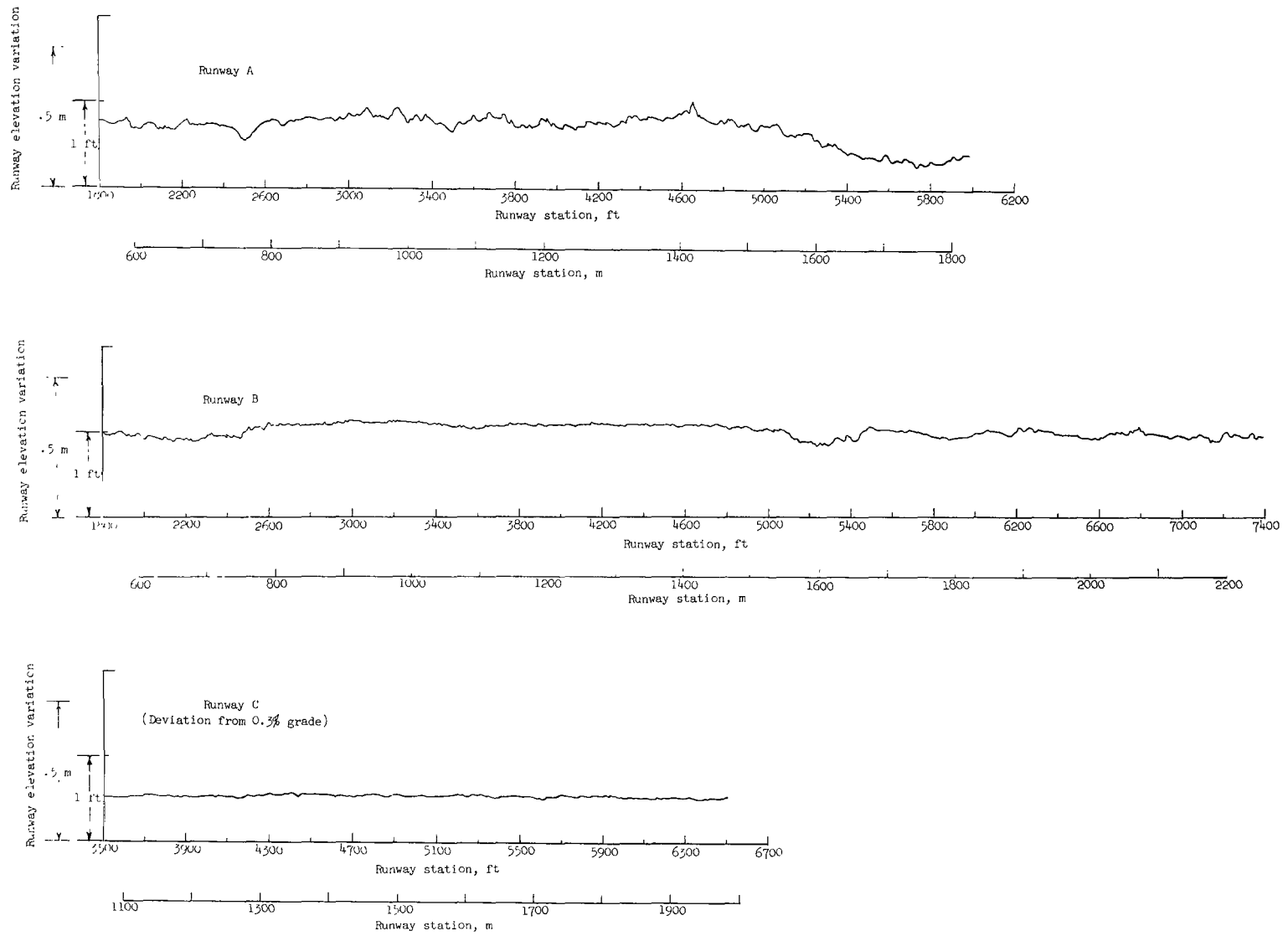
Figure 6.- Profiles for test sections of runways A, B, and C.
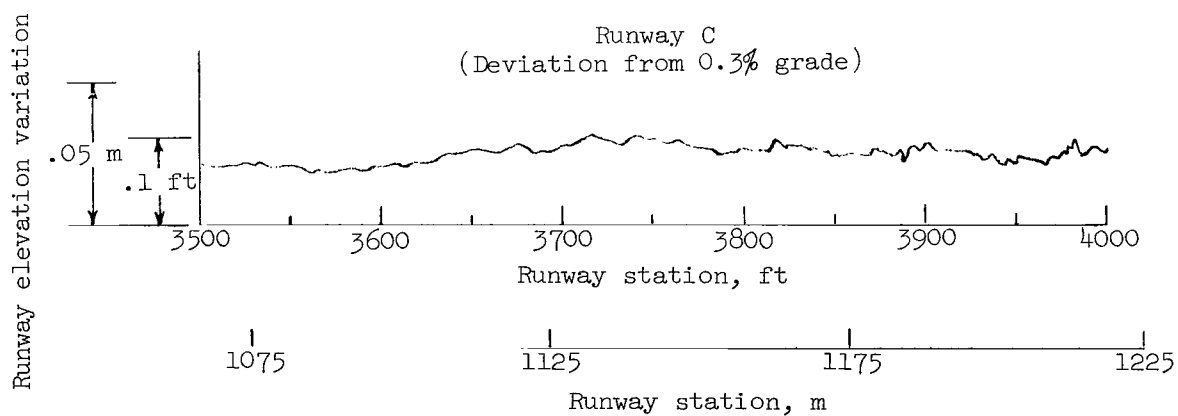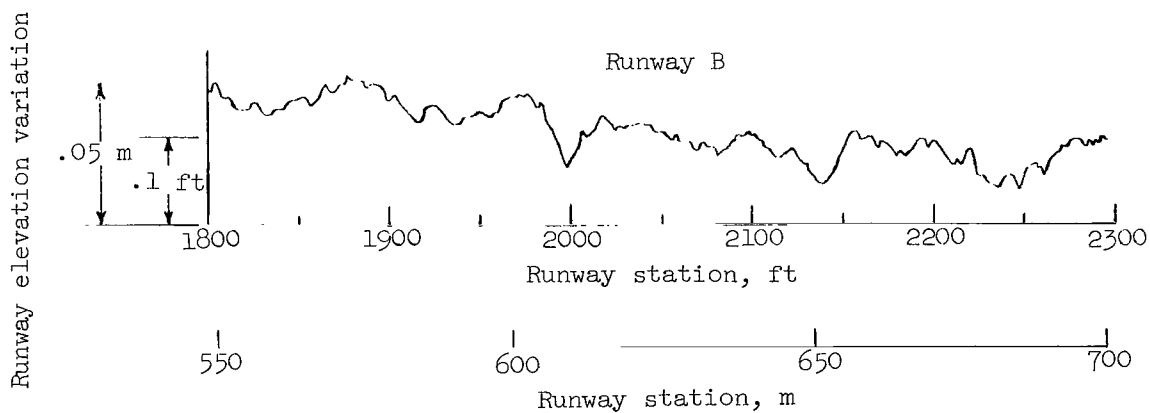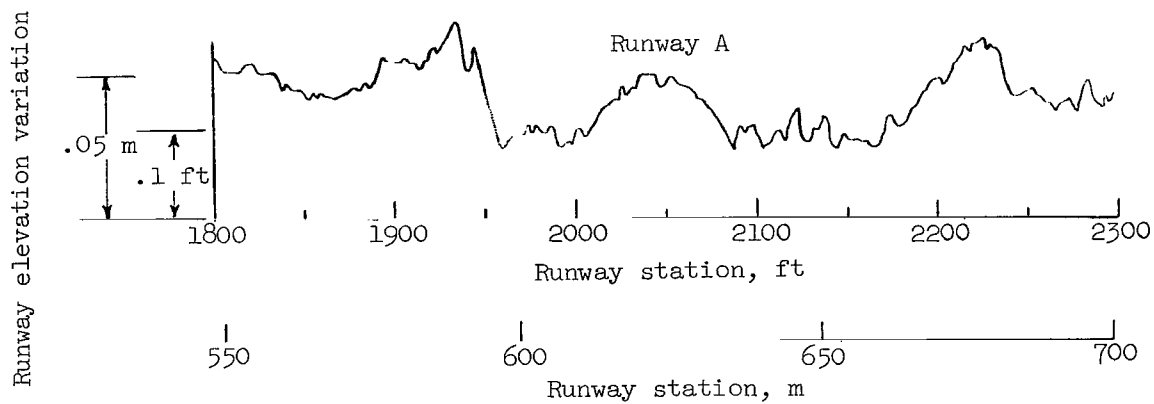
Figure 7.- Profiles for part of test sections of runways A, B, and C.

Wavelength, λ, m

Reduced frequency, Ω, radians/meter

Power spectral density, $\Phi_h(\Omega)$

Runway

A

B

C

New construction

Reduced frequency, Ω, radians/ft

Wavelength, λ, ft
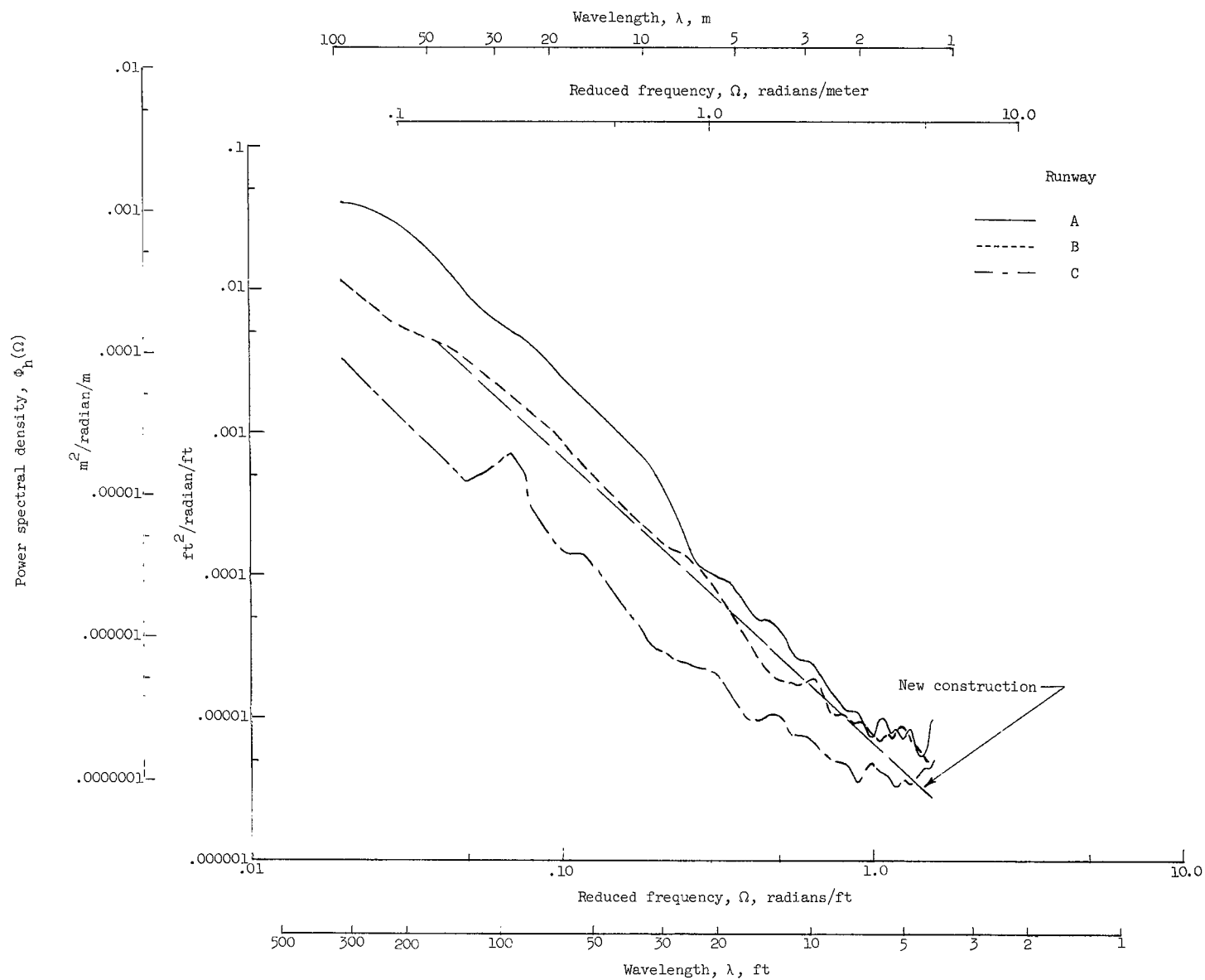
Figure 8.- Power-spectral-density functions for profiles of test sections of runways used in investigation.

Pitching velocity, q

Acceleration, g units

deg/sec

2
0
-2

Transverse a_t

.5
0
-.5

Pilot compartment

Normal a_n

5
0
-.5

Pilot compartment

Normal a_n

.5
0
-.5

Center of gravity

|←1 sec→|

Runway elevation variation

Direction of taxiing ⟶

.05 m
.1 ft

1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000

Runway station, ft

600   700   800   900   1000   1100   1200

Runway station, m
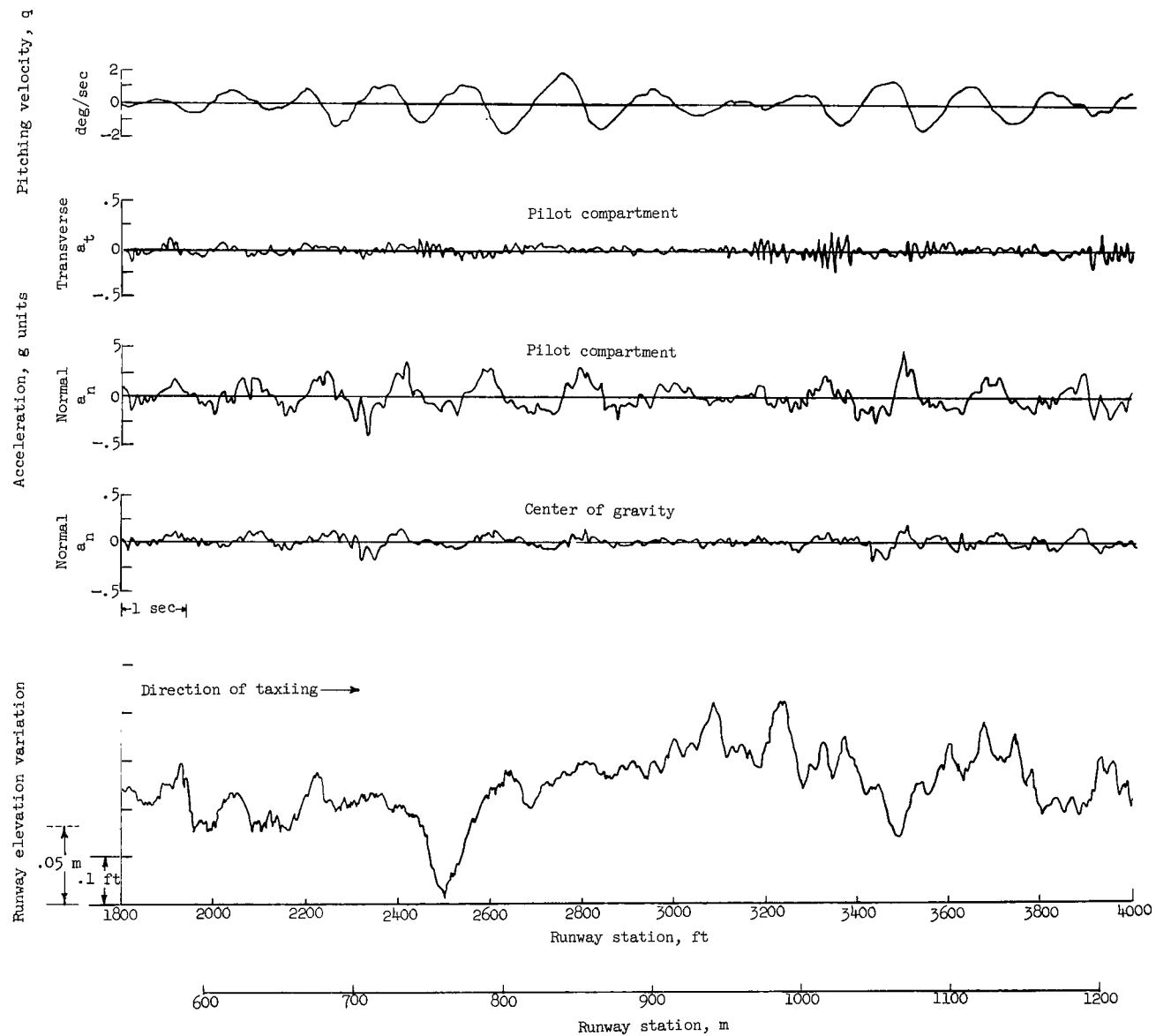
Figure 9.- Runway center-line elevation variation and resulting turbojet-transport-airplane response for 2200-foot (671 m) section of runway A at 82 knots.
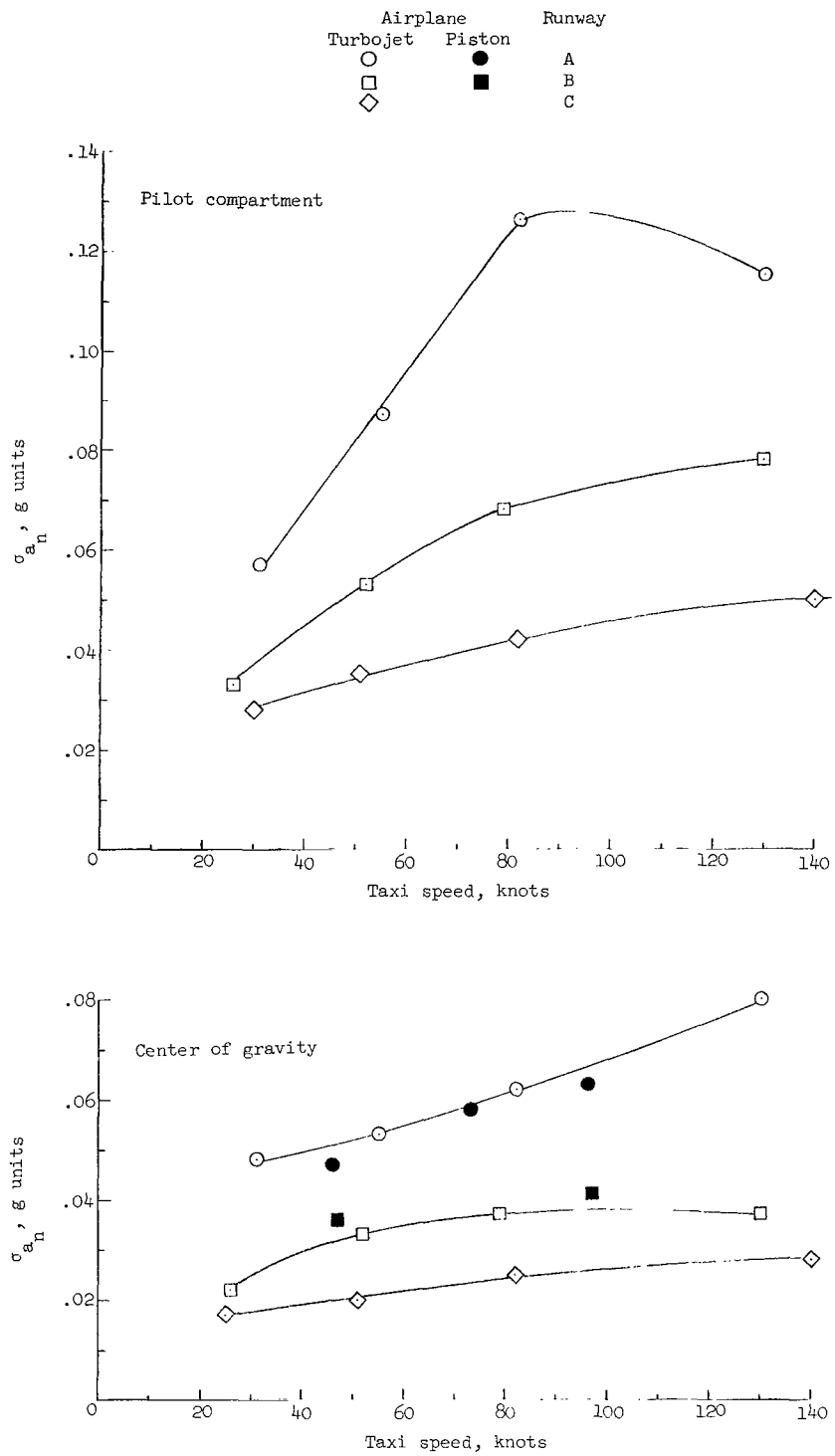
Figure 10.- Root-mean-square values of normal-acceleration response of test airplanes for various taxi speeds.

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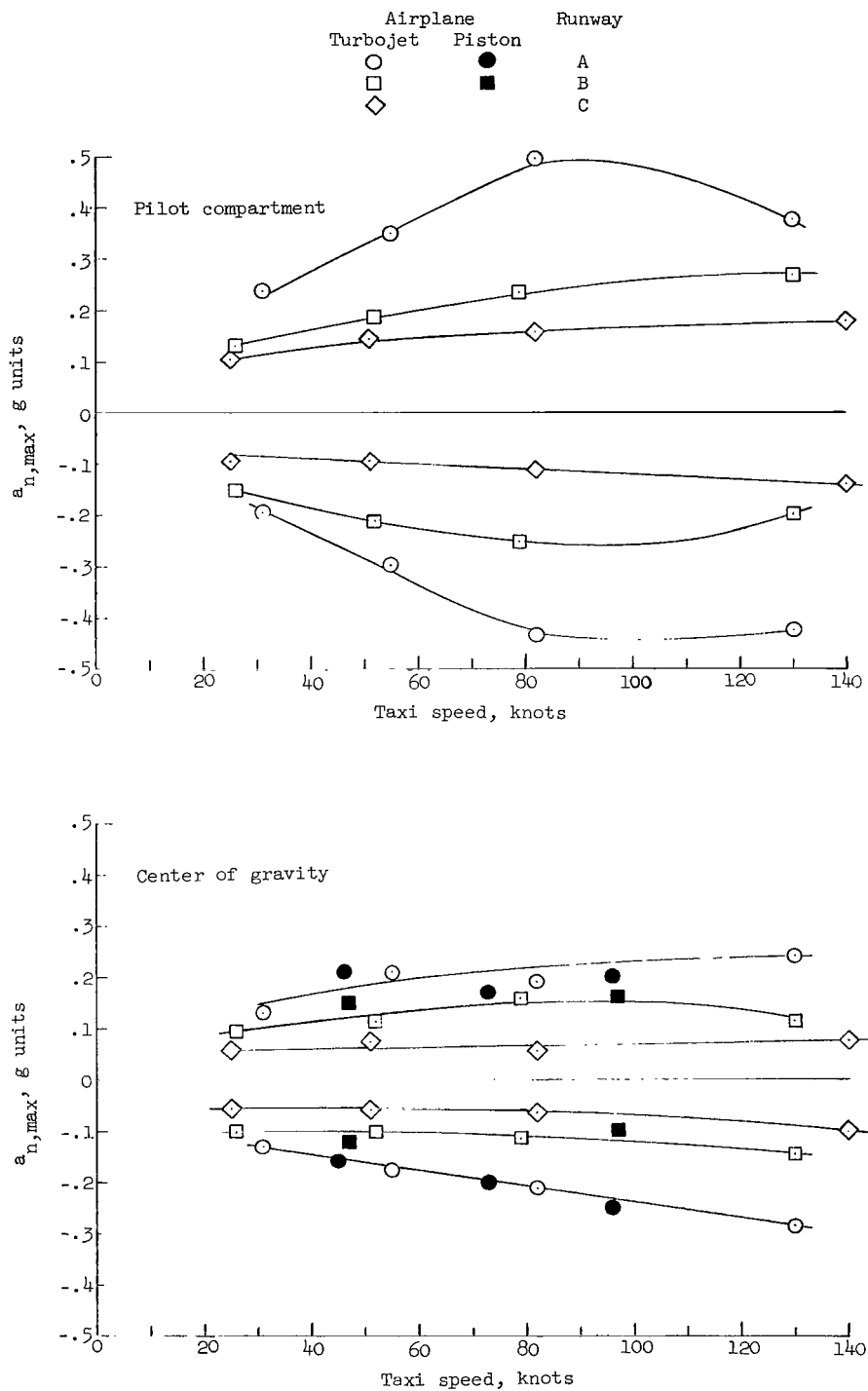
Figure 11.- Maximum values of normal-acceleration response of test airplanes for various taxi speeds.
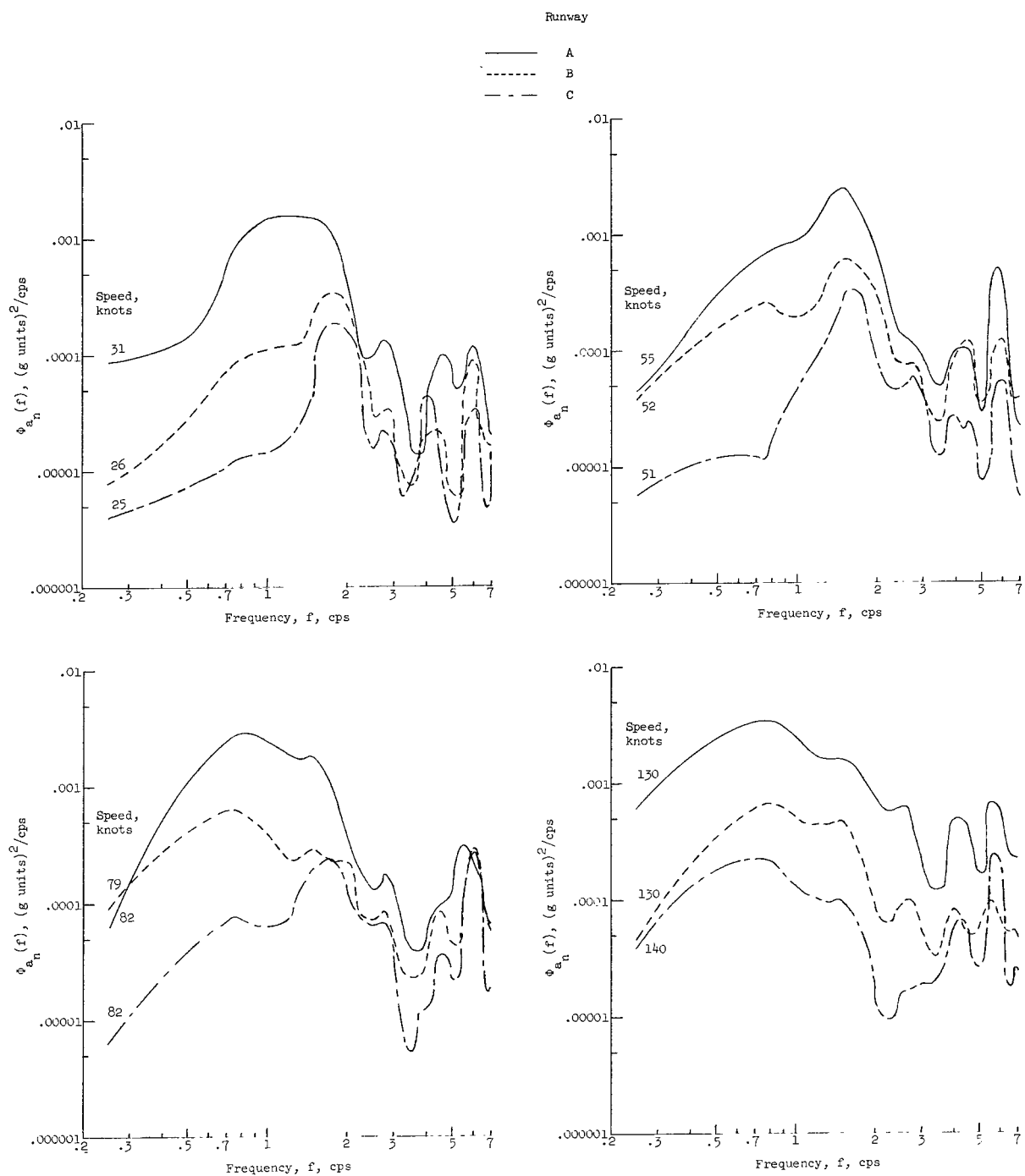
(a) Acceleration at center of gravity.

Figure 12.-   Power-spectral-density functions of turbojet-airplane normal-acceleration response at various taxi speeds on runways A, B, and C.
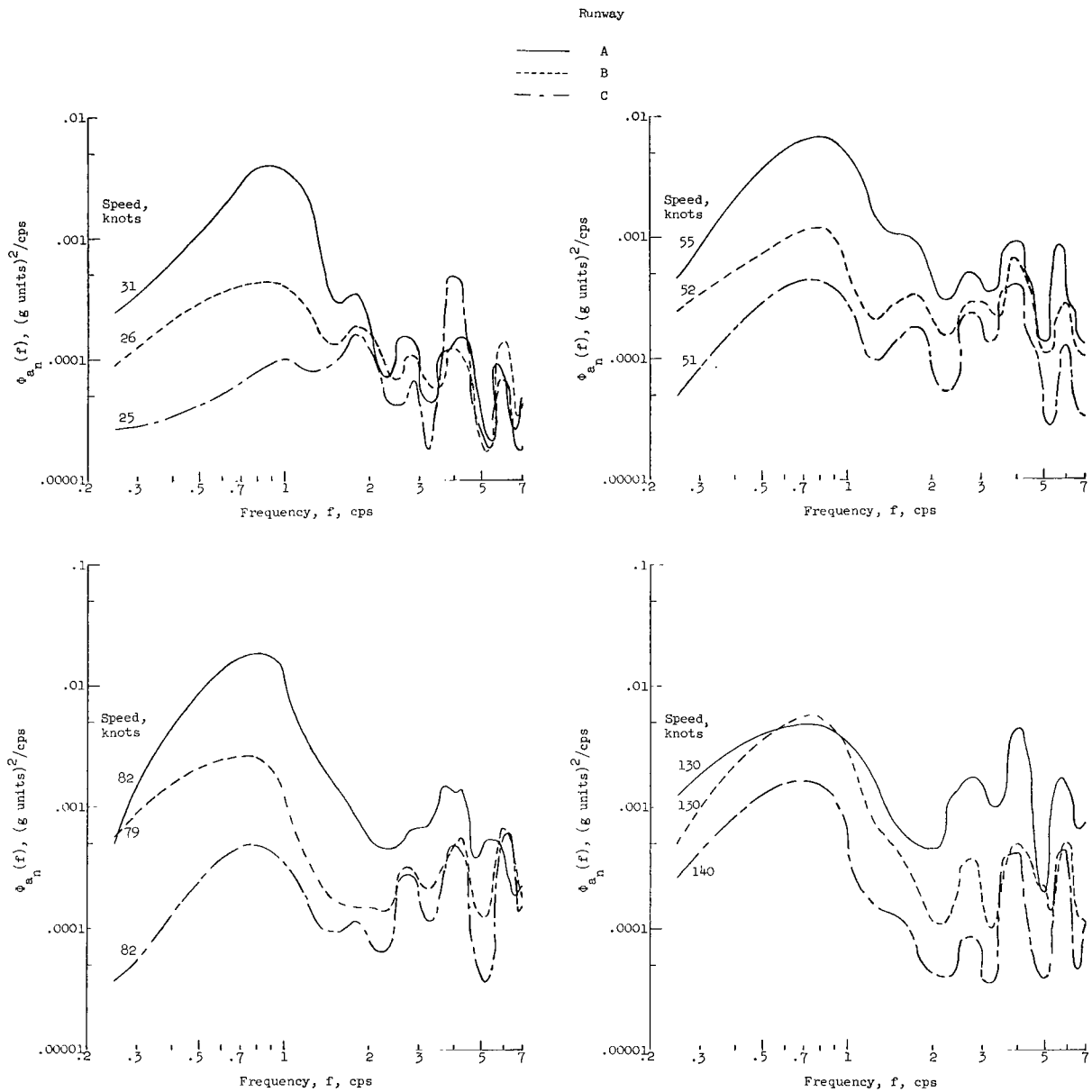
(b) Acceleration in pilot compartment.

Figure 12.- Concluded.
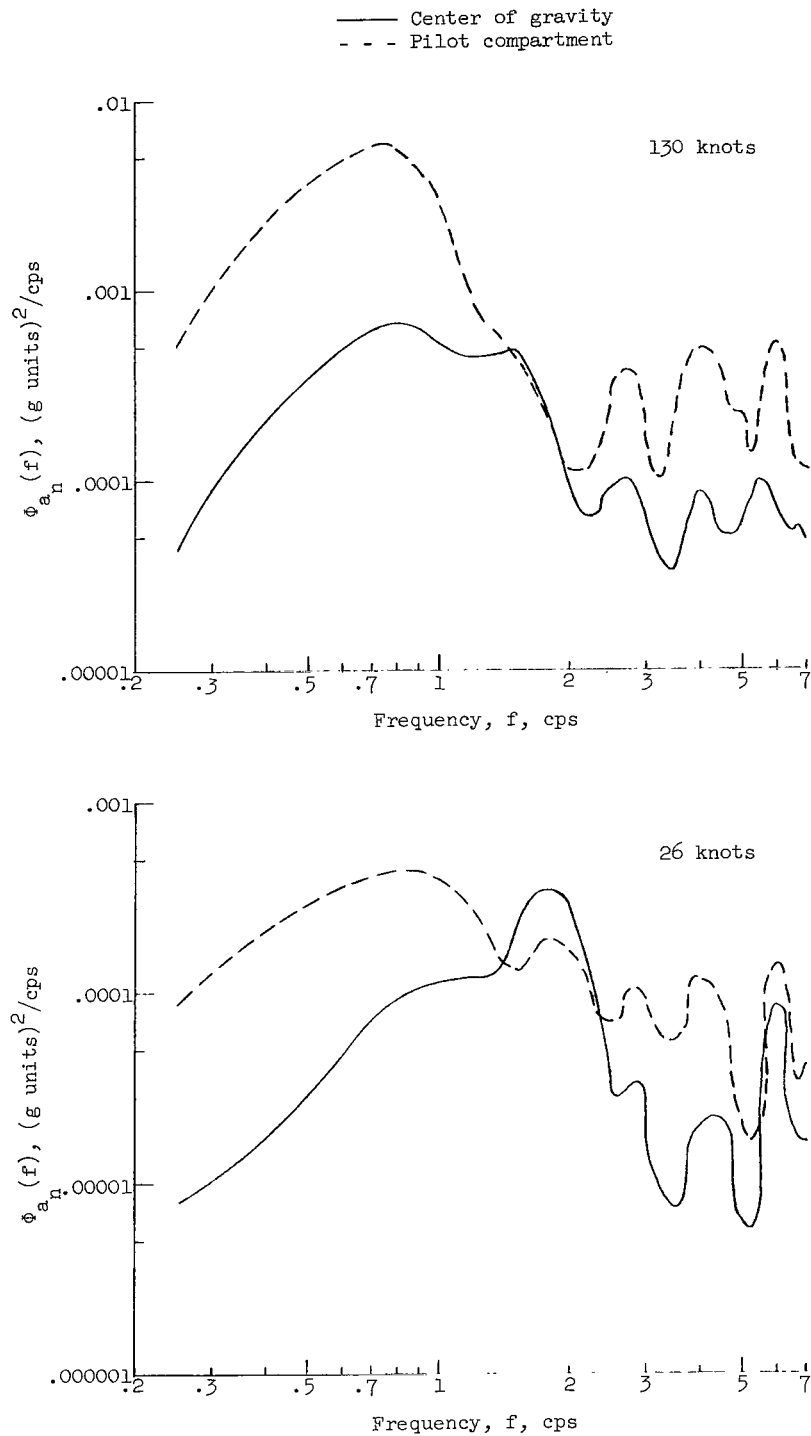
Figure 13.- Comparison of power-spectral-density functions of airplane normal acceleration near the center of gravity and in the pilot compartment of the turbojet transport on runway B.

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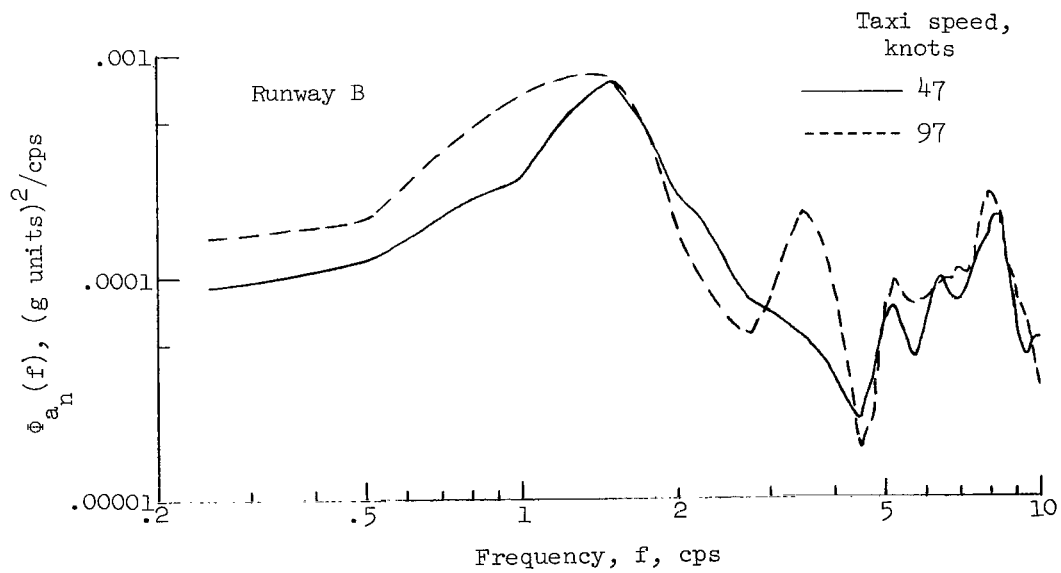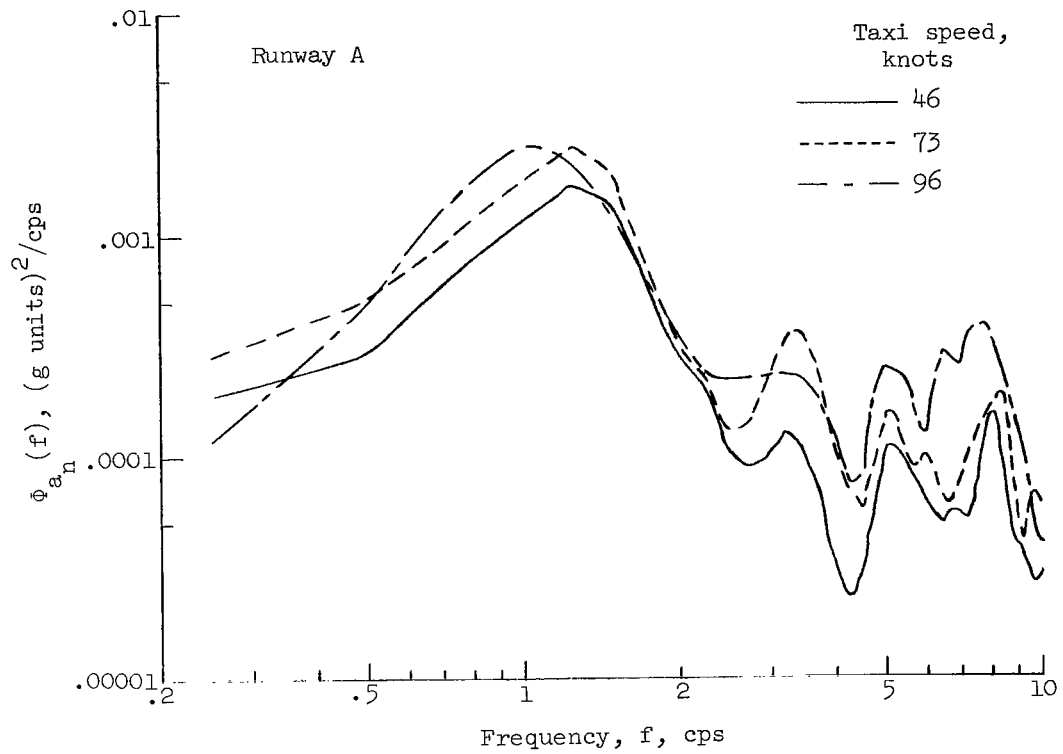
Figure 14.- Power-spectral-density functions of normal-acceleration response near the center of gravity of a small piston-engine transport airplane on runways A and B.
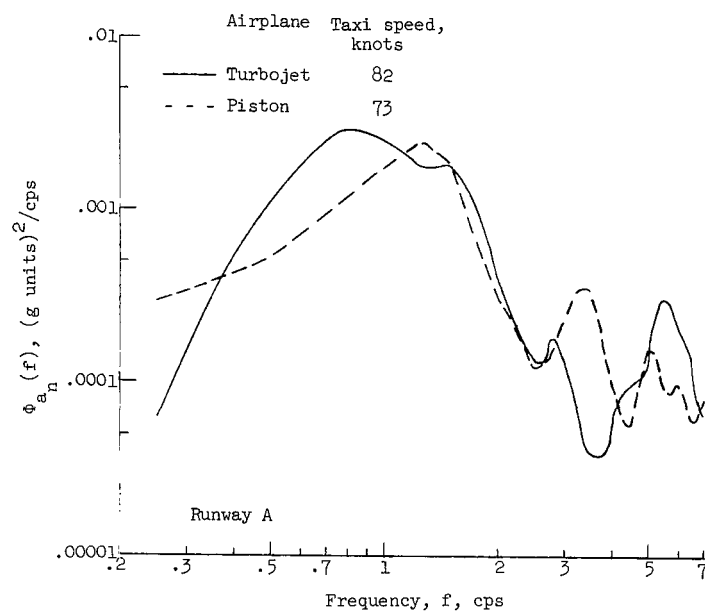
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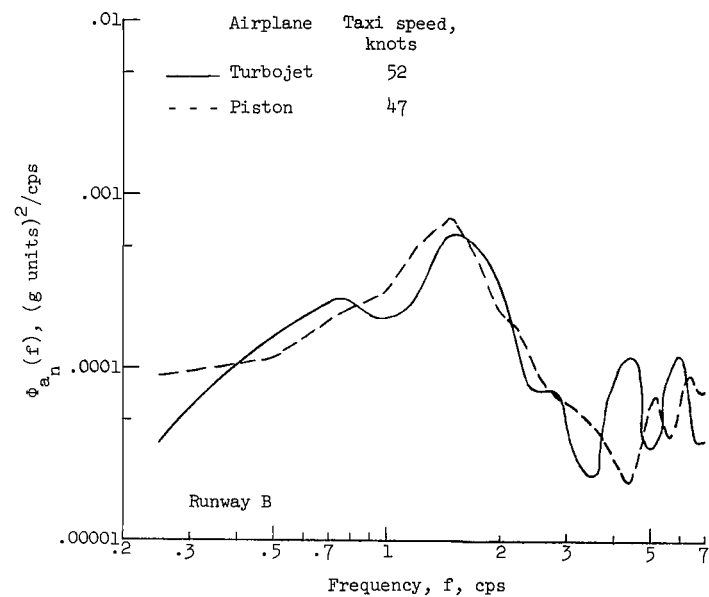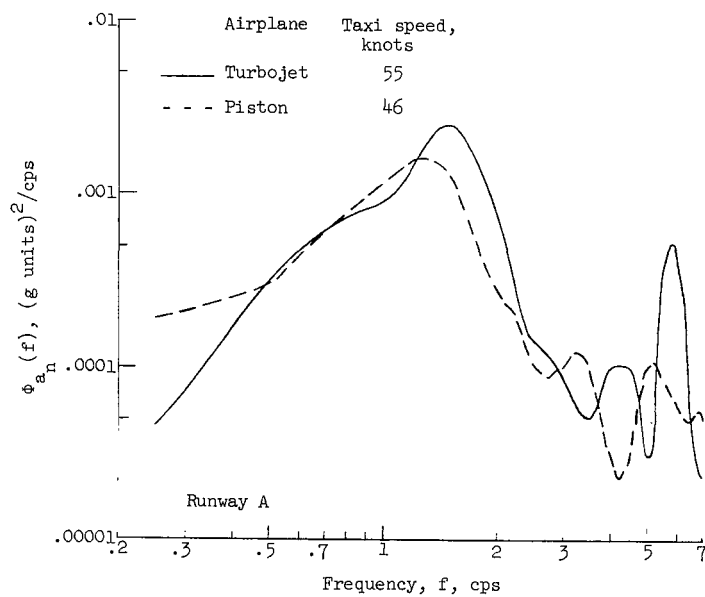
Figure 15.- Comparison of power-spectral-density functions of normal-acceleration response near center of gravity of turbojet and piston-engine airplanes at similar speeds on runways A and B.
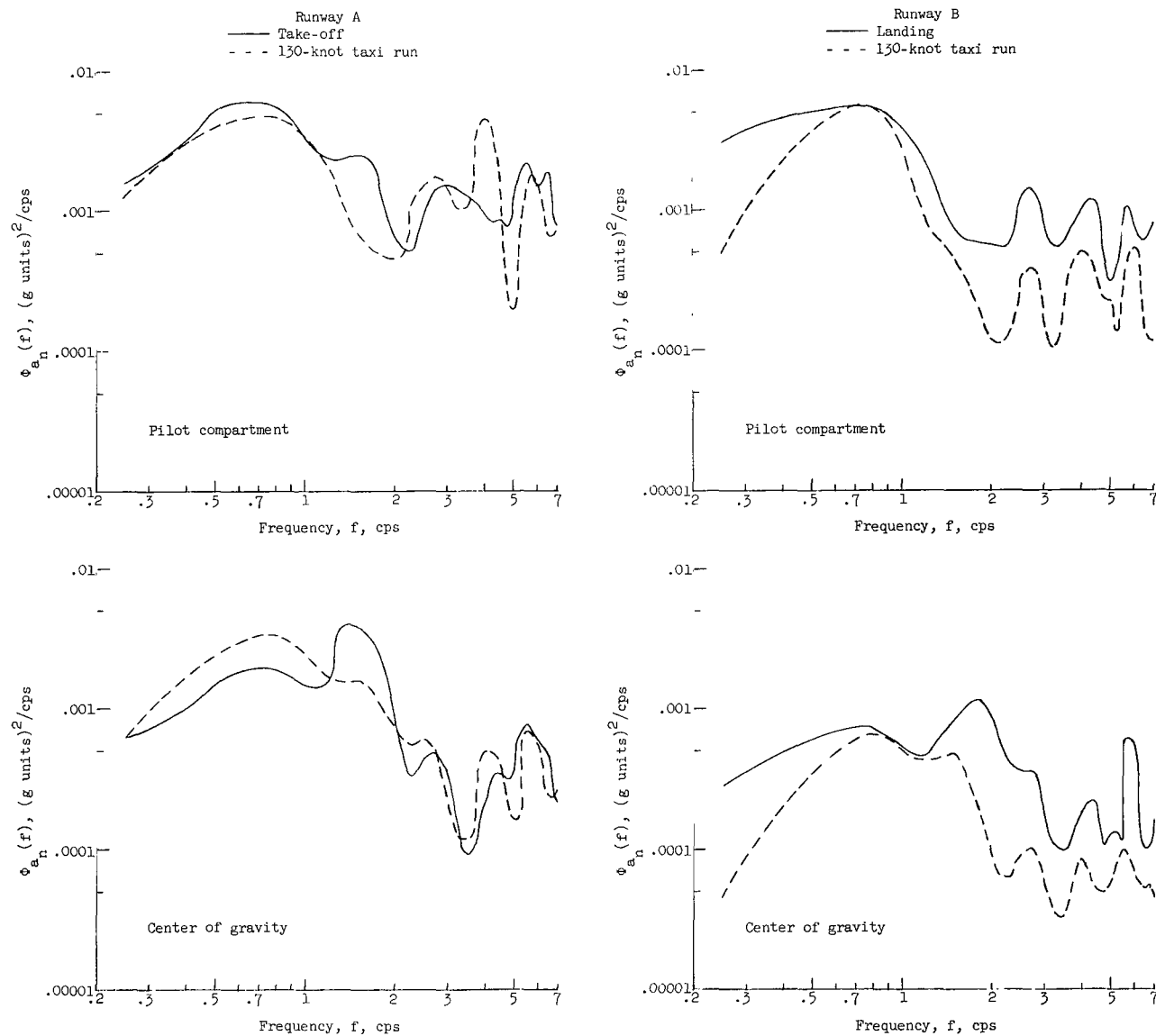
Figure 16.   Power-spectral-density functions of normal-acceleration response of a turbojet transport airplane during a landing, a take-off, and high-speed taxiing runs.
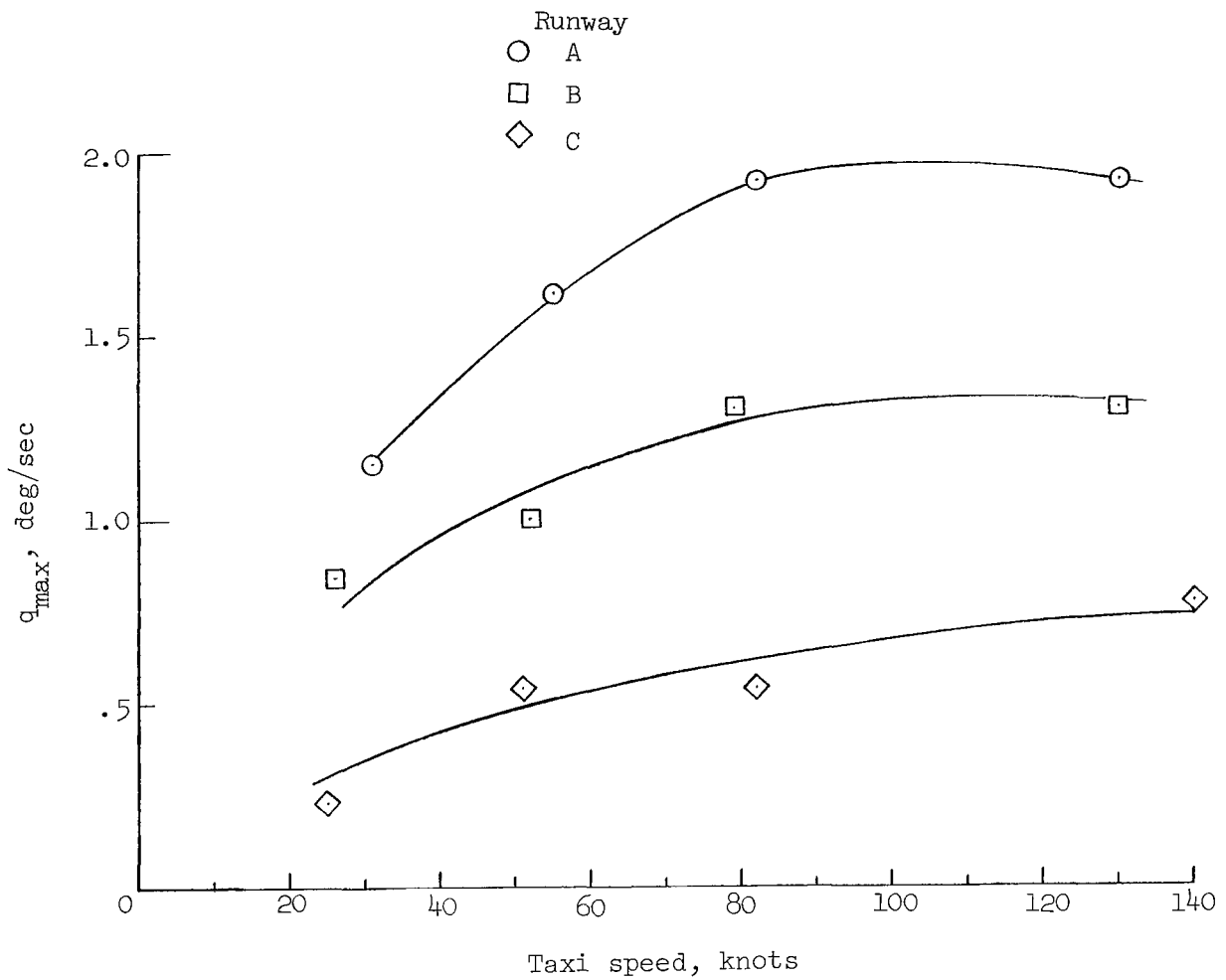
Figure 17.- Maximum values of pitching velocity of turbojet airplane at various taxi speeds on runways A, B, and C.
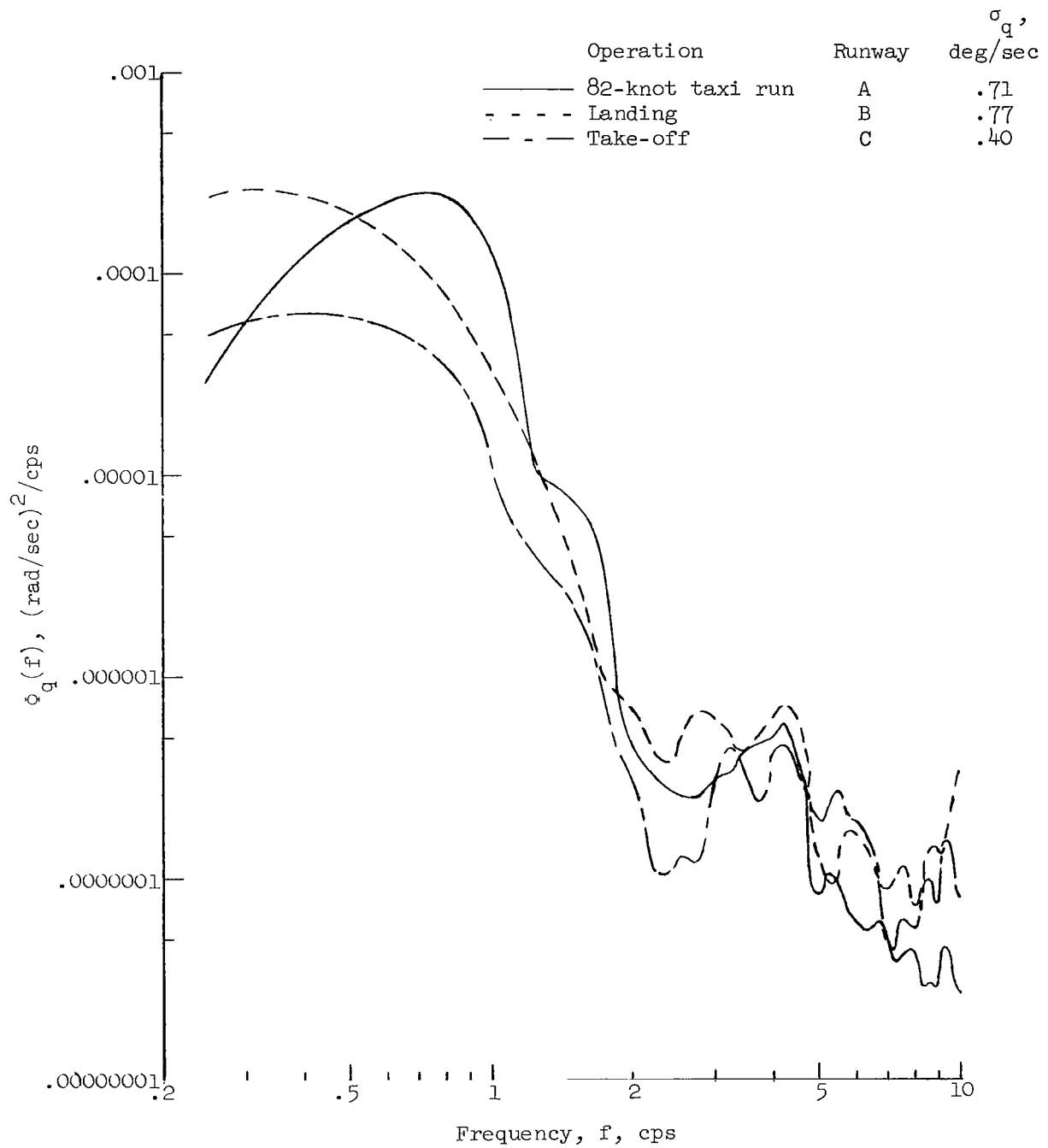
Figure 18.- Power-spectral-density functions of pitching-velocity response of turbojet airplane.
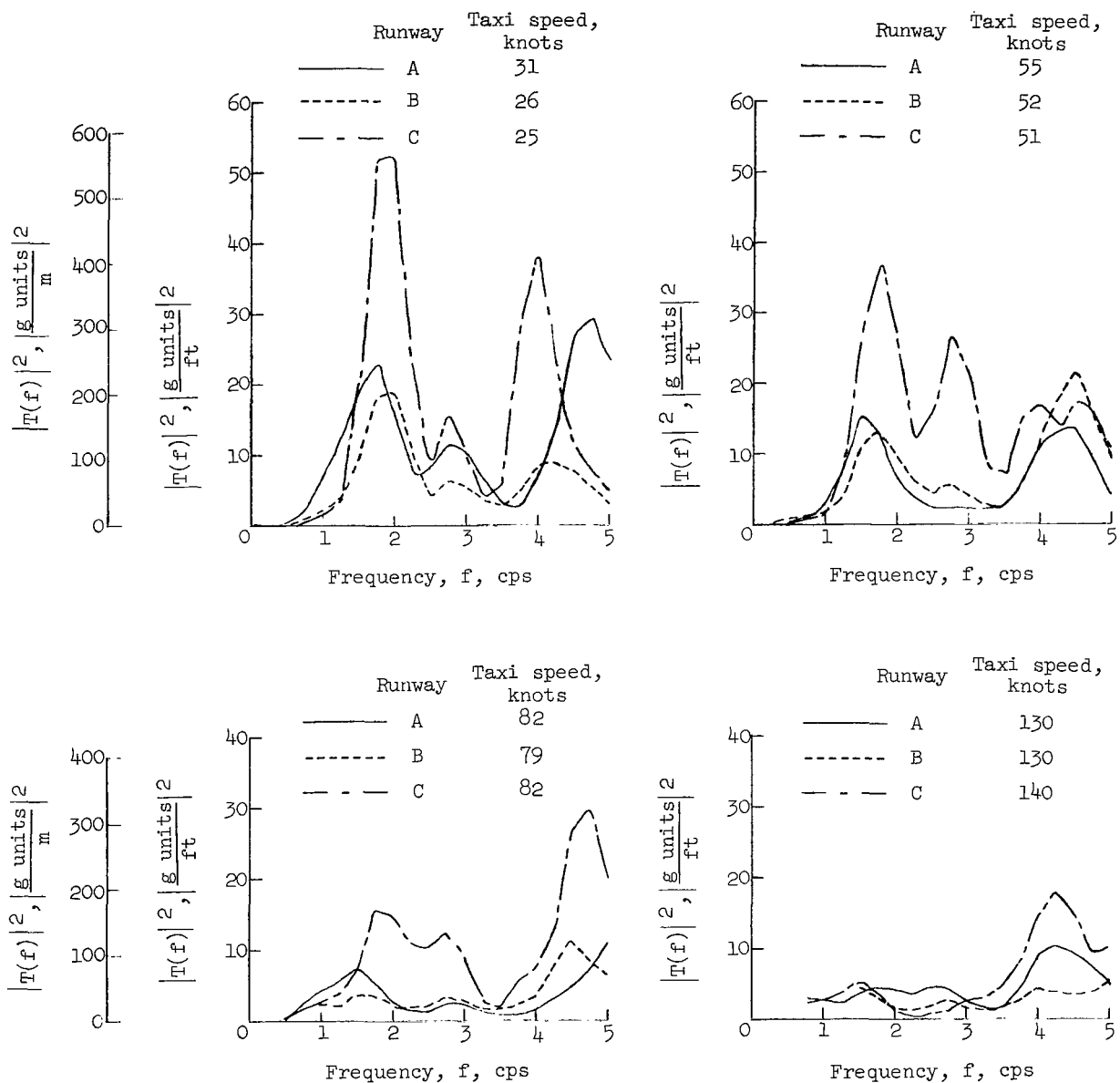
Figure 19.- Transfer functions of airplane center-of-gravity normal acceleration for taxi runs of turbojet transport on test runways.

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