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MEMORANDUM

STUDY OF TAXIING PROBLEMS ASSOCIATED

WITH RUNWAY ROUGHNESS

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NATIONAL AERONAUTICS AND
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Runway Profiles

Some idea of the roughness which may be encountered by airplanes can be gained by examining some typical runway profiles (fig. 1). For clarity the elevations are greatly magnified with respect to the horizontal distance, adjacent ticks representing an increment in elevation of 0.05 foot or 0.6 inch. The uppermost profile is a section from a former runway, now inactive as a runway but used as a taxiway. This particular taxiway is the worst of the 50 or so profiles that have been analyzed to date. Next is a profile from a runway which shall be called "runway X." Runway X is an active operational runway that is supposed to be good from an engineering standpoint but has caused pilots' complaints. The third plot shows a length of a very good commercial runway at a large international airport. Finally, a profile is shown of the pavement of the landing loads track at the Langley Research Center, which had to be very smooth for use in research.

The wide range of roughness from top to bottom of figure 1 is immediately evident. Closer inspection shows that each profile is composed of a jumble of superimposed waves of different wave lengths, the amplitudes generally becoming larger as the wave lengths increase.

These elevation profiles give a qualitative idea of the surface roughness but for technical analysis quantitative information regarding the variation of the amplitude of the waves with the wave length is needed. One way of showing this relationship is by means of the power spectrum, a form of which is presented in figure 2. For the present purposes, the ordinate Φ can be considered simply as an index of the relative amplitudes corresponding to the wave lengths shown on the abscissa. As expected, the uppermost curve is for the rough taxiway, whereas the spectra for the Langley landing loads track and the commerical runway fall considerably lower. Runway X, although better than the commercial runway at long wave lengths, appears to be almost as bad as the rough taxiway at intermediate wave lengths where the data end.

Since landing gears transmit the greatest loads when the impressed frequencies are between 1.5 and 2 cycles per second, the critical runway wave length corresponding to any given taxi speed can now be defined. If the speed range from 20 to 130 knots is considered, the critical wave lengths are found to lie between 17 and 150 feet. This region is of greatest concern, since the landing-gear response will be much reduced outside this range.

Taxi Loads

Figure 3 is a statistical presentation showing the frequency of occurrence of the loads that an airplane might experience in taxiing over the different types of runway in, for instance, 1,000 flights. The ordinate is the cumulative frequency of occurrence; that is, the number of acceleration peaks, both plus and minus, that will reach or exceed a given level in 1,000 flights. The solid-line curve is based on an analysis of a large amount of VGH data obtained in airline operations and might be considered as a national average. The other curves were derived from theoretical studies of taxiing on the four runways previously discussed and are based on a taxi speed of 30 knots. The end point at the zero-g level represents the total number of acceleration peaks experienced during the exposure time involved.

If all the taxiing were done on the rough taxiway, the loads would be about 3 times as high as the national average. Runway X, which has produced some complaints, appears to be comparable to the national average, whereas the good commercial runway and the Langley landing loads track would impose considerably smaller loads on the airplane. The implications regarding fatigue problems which may be caused by the different levels of roughness are self evident.

The effect of airplane taxi speed on the loads is illustrated in figure 4. The ordinate is the average acceleration amplitude resulting from traversing a given runway at a particular speed. The curves, again, are based on theoretical studies of taxiing over the four runways under consideration. The three experimental points shown were obtained from acceleration records of taxi tests of an F-100 airplane over runway X and give some confidence in the theoretical results. For reference, the straight line on the left represents the average acceleration amplitude from the VGH records of airline operations. Again, the rough taxiway is seen to be very rough. The accelerations for runway X are slightly above the national average throughout most of the speed range. The good commercial runway may begin to cause trouble at very high speeds. It is evident from these results that the variation of the acceleration with speed is closely dependent on the detailed characteristics of the runway. Thus to answer one of our questions, there isn't much the pilot can do about reducing the loads on a rough runway except to taxi at very low speeds.

From the fact that runway X has caused complaints and also lies close to the national average, the airline data can be used to derive some rough inferences regarding the levels of acceleration that might be considered as limits for a satisfactory runway; on this basis, the average acceleration amplitudes for the usual range of operating speeds

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SUMMARY

This paper briefly summarizes available statistical data on airplane taxi operations, examines the profiles and power spectra of four selected runways and taxiways covering a wide range of surface roughness, considers (on the basis of theoretical and experimental results) the loads resulting from taxiing on such runways over a range of speeds and, by synthesis of the aforementioned results, proposes new criteria for runway and taxiway smoothness which are applicable to new construction and may also be used as a guide for determining when repairs are necessary.

INTRODUCTION

The motions and loads caused by runway and taxiway irregularities can produce a broad spectrum of operating difficulties, ranging from fatigue damage and structural failures to pilots' complaints. Recent trends in airplane design, such as increased structural flexibility and the use of large external stores, have served to aggravate the situation.

For some time, a research program has been in progress for the study of various aspects of the runway-roughness problem, such as the statistics of taxiing operations, the dynamics of the landing gear in taxiing, and the roughness characteristics of many runways in this country and abroad, the latter with the aid of surveys provided by countries of the North Atlantic Treaty Organization through the Advisory Group for Aeronautical Research and Development.

Because existing criteria for runway surface smoothness are largely subjective, much attention is being given to the development of improved criteria on a more rational engineering basis. Three questions that require answers are:

(1) At what level does roughness become a problem?
(2) How should runway surfaces be specified?
(3) Is there anything the pilot can do to minimize the effects of roughness?

Recent research has provided information which may be used to answer these questions and the present paper attempts to summarize current thinking on the subject.

RESULTS AND DISCUSSION

VGH Data

To begin with, a few simple statistical results are presented in the following table:

AIRLINE EXPERIENCE

(Based on VGH-Recorder Data)

Taxiing time	Approximately 5 minutes
Time on taxiways	80 percent
Primary response	1.5 to 2 cps

Study of many VGH records from airline operations shows that the amount of time spent in taxiing is remarkably constant, approximately 5 minutes per flight (the word "flight" including one departure and one arrival). Very significantly, about 80 percent of this 5 minutes of taxiing is done on taxiways. Available flight records also show that for a wide range of airplanes, regardless of size and mission, the predominant response of the landing gear occurs in a very narrow frequency range, between 1.5 and 2 cycles per second; and this includes data from fighters, transports, and heavy bombers. Theoretical studies of landing-gear dynamics also show the same narrow sensitivity band. For frequencies outside this band, the landing gear provides relatively good isolation of the airplane from ground disturbances. The fact that the sensitive range is virtually always between 1.5 and 2 cycles per second is due to the standardized way in which tires are specified and shock-strut compression ratios are normally chosen.

should not exceed about $\frac{1}{8}$g (fig. 4), and the maximum acceleration at speeds around 30 knots should not exceed about $\frac{1}{2}$g (fig. 3).

Specification of Surface Smoothness

In the specification of runway-surface smoothness, current practice generally requires that the maximum deviation from a 10-foot straight edge shall not exceed 1/8 inch. Frequently, a second requirement is specified - the deviation from the theoretical grade line shall not be more than ±0.04 foot; that is, about ±1/2 inch. A better way of specifying a runway can be suggested, and for this purpose, figure 5 is presented. By simple mathematical manipulation (appendix A) of the power spectra shown previously, the average peak amplitude σ' of the roughness within any given horizontal distance l can be determined. Such calculations have been made for three of the runways previously discussed. Unfortunately, this type of calculation was not possible for runway X because of certain limitations in the available data.

The derived curves for the commercial runway and the Langley landing-loads track are in close agreement with the actual specifications used for their construction. In the case of the commercial runway the calculated peak amplitude over 10 feet is 0.005 foot, which corresponds very closely with the 1/8-inch deviation from a 10-foot straight edge which was specified. In the case of the landing loads track, the calculated peak amplitude is practically constant and corresponds closely with the construction specification which limited the deviations to ±1/8 inch from a given level surface throughout the entire length of the pavement.

The foregoing results suggest some new criteria for runway smoothness. Since a well-defined band of critical wave lengths exists, it must be taken into account by the specifications. Thus, deviations from a straight line must be limited over a length of 17 feet and over a length of 150 feet. In order to maintain control over the intermediate wave lengths, deviations over a length of 80 feet are also specified. As a specification for new construction, the commercial runway can be used as a guide, at least up to a length of 80 feet. At 150 feet a greater degree of smoothness should be obtainable so that a value closer to that of the Langley landing-loads track is specified. The values chosen for new construction are shown in figure 5 by the circles and are tabulated in terms of maximum deviation from a straight edge, in fractions of an inch. Over a 17-foot length, the maximum deviation $2\sigma'$ should not exceed 5/32 inch; over an 80-foot length, the limit is

9/32 inch; and over a 150-foot length, the deviation should not exceed 11/32 inch.

Also needed is a guide to determine when a runway should be repaired. Working back from the airline data and the complaints regarding runway X has led to the conclusion that repairs are indicated when the deviations become about twice as large as those specified for new construction. The power spectra corresponding to these requirements are indicated by the two dotted lines superimposed on the spectra shown previously (fig. 6).

One last point should not be overlooked. Since airplanes spend about 80 percent of their taxi time on taxiways, it will be of little help to improve runways unless taxiways are similarly improved. It is therefore suggested that taxiways be built and maintained to the aforementioned specifications, with one exception. Since operation on taxiways will generally not be at the high speeds used on runways, the 150-foot requirement may be waived without detriment.

It goes without saying that the practice of using old abandoned rough runways as taxiways should be discouraged.

CONCLUDING REMARKS

This paper has briefly summarized available statistical data on airplane taxi operations, examined the profiles and power spectra of four selected runways and taxiways covering a wide range of surface roughness, considered (on the basis of theoretical and experimental results) the loads resulting from taxiing on such runways over a range of speeds and, by synthesis of the aforementioned results, has proposed new criteria for runway and taxiway smoothness which are applicable to new construction and may also be used as a guide for determining when repairs are necessary.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., November 5, 1958.

APPENDIX A

DETERMINATION OF AVERAGE PEAK ROUGHNESS AMPLITUDE

This appendix briefly outlines the method used for manipulating the runway power spectra to determine the average peak amplitude σ' of the roughness over any given distance l (fig. 5), which provides the basis for the proposed specifications for surface smoothness.

By definition, the power spectral density $\phi \left(\frac{ft^2}{radian/ft}\right)$ represents the mean-square value σ^2 of the amplitudes contained in the frequency components between Ω and $\Omega + d\Omega$, where Ω is the reduced frequency (radians/ft) and is related to the wave length λ (ft) by $\Omega = \frac{2\pi}{\lambda}$. Thus, integration of ϕ over any frequency band yields the mean-square value of the amplitudes within that frequency band; that is,

$$\sigma^2(\Omega_1,\Omega_2) = \int_{\Omega_1}^{\Omega_2} \phi \, d\Omega$$

or, in terms of the wave length,

$$\sigma^2(\lambda_1,\lambda_2) = 2\pi \int_{\lambda_2}^{\lambda_1} \frac{\phi}{\lambda^2} \, d\lambda$$

where $\lambda_1 = \frac{2\pi}{\Omega_1}$ and $\lambda_2 = \frac{2\pi}{\Omega_2}$.

Since the mean-square value of the roughness up to a given wave length l encompasses all wave lengths between $\lambda = 0$ and $\lambda = l$ $\left(\text{reduced frequencies between } \Omega = \infty \text{ and } \Omega = \frac{2\pi}{l}\right)$,

$$\sigma^2(l) = \int_{\Omega=\frac{2\pi}{l}}^{\infty} \phi \, d\Omega = 2\pi \int_{\lambda=0}^{l} \frac{\phi}{\lambda^2} \, d\lambda \tag{A1}$$

Random-process theory indicates that, on the average, the maximum excursion (peak amplitude) $\sigma'(l)$ of the roughness over the length l is related to the root-mean-square value $\sigma(l)$ by a form factor k; that is,

$$\sigma'(l) = k\sigma(l)$$

where the value of k depends on the detailed characteristics of the roughness and the length l.

Examination of a number of actual runway profiles indicates that the form factors over the range of critical lengths (17 to 150 feet, as discussed in the text) are generally in the neighborhood of that for a simple sine wave; that is, $k \approx \sqrt{2}$.

The values of average peak roughness amplitude given in figure 5 were accordingly determined by integrating the runway power spectra in accordance with equation (A1) to obtain the mean-square value $\sigma^2(l)$ and calculating the average peak amplitude from the relationship $\sigma'(l) = \sqrt{2}\sigma(l)$.

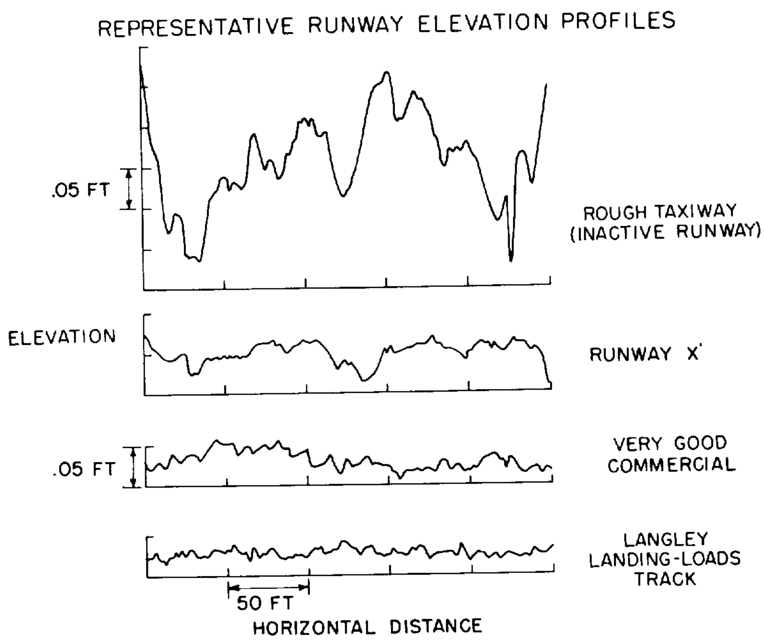


Figure 1

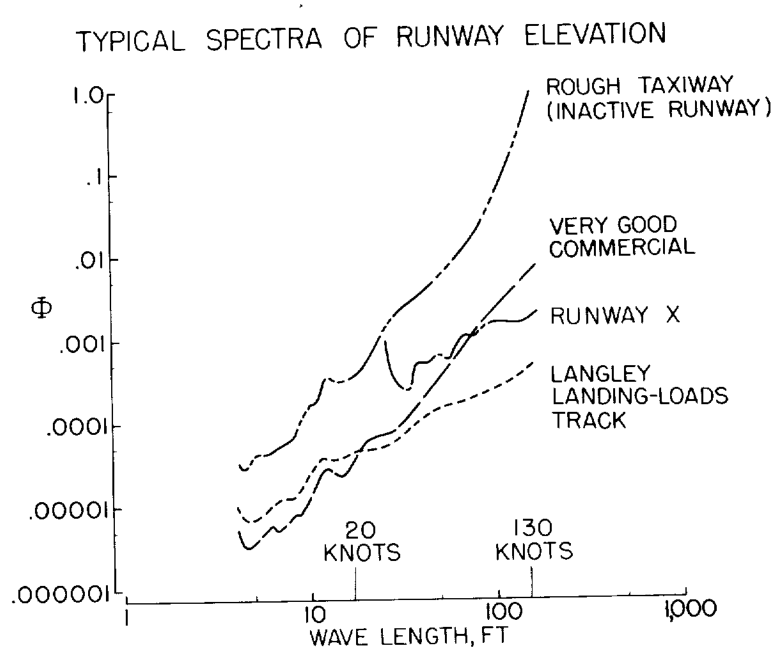


Figure 2

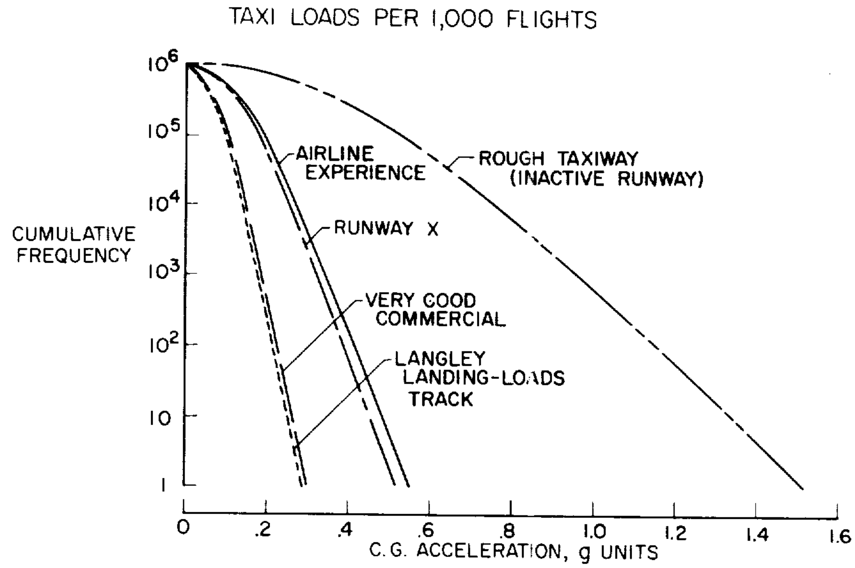


Figure 3

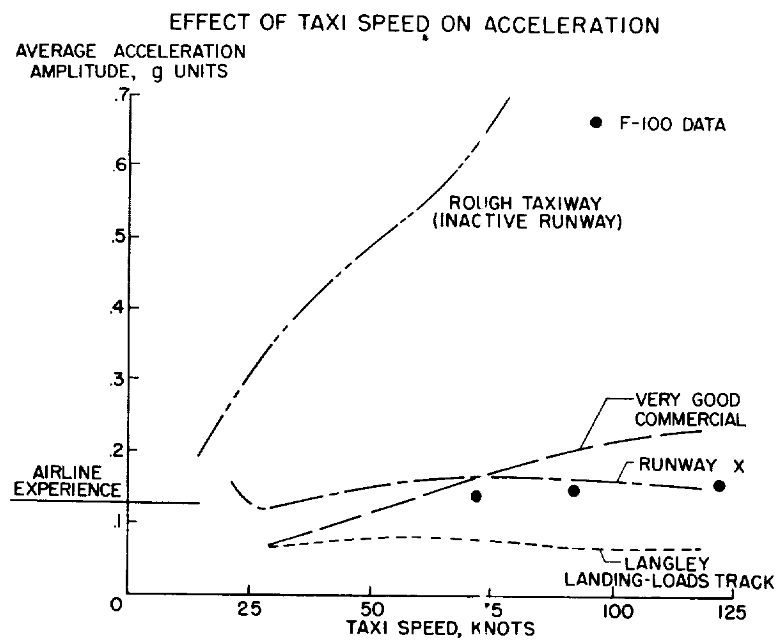


Figure 4

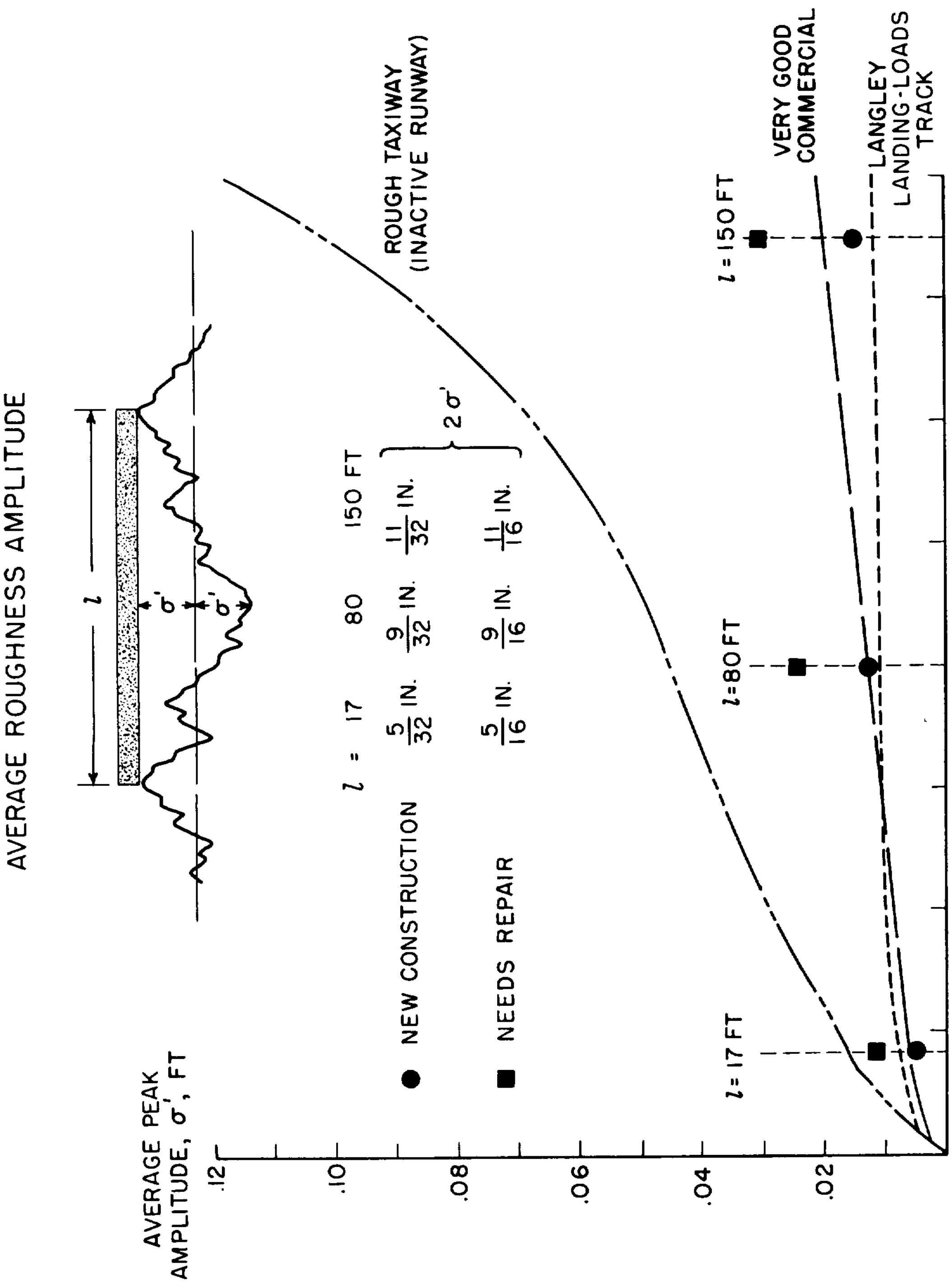
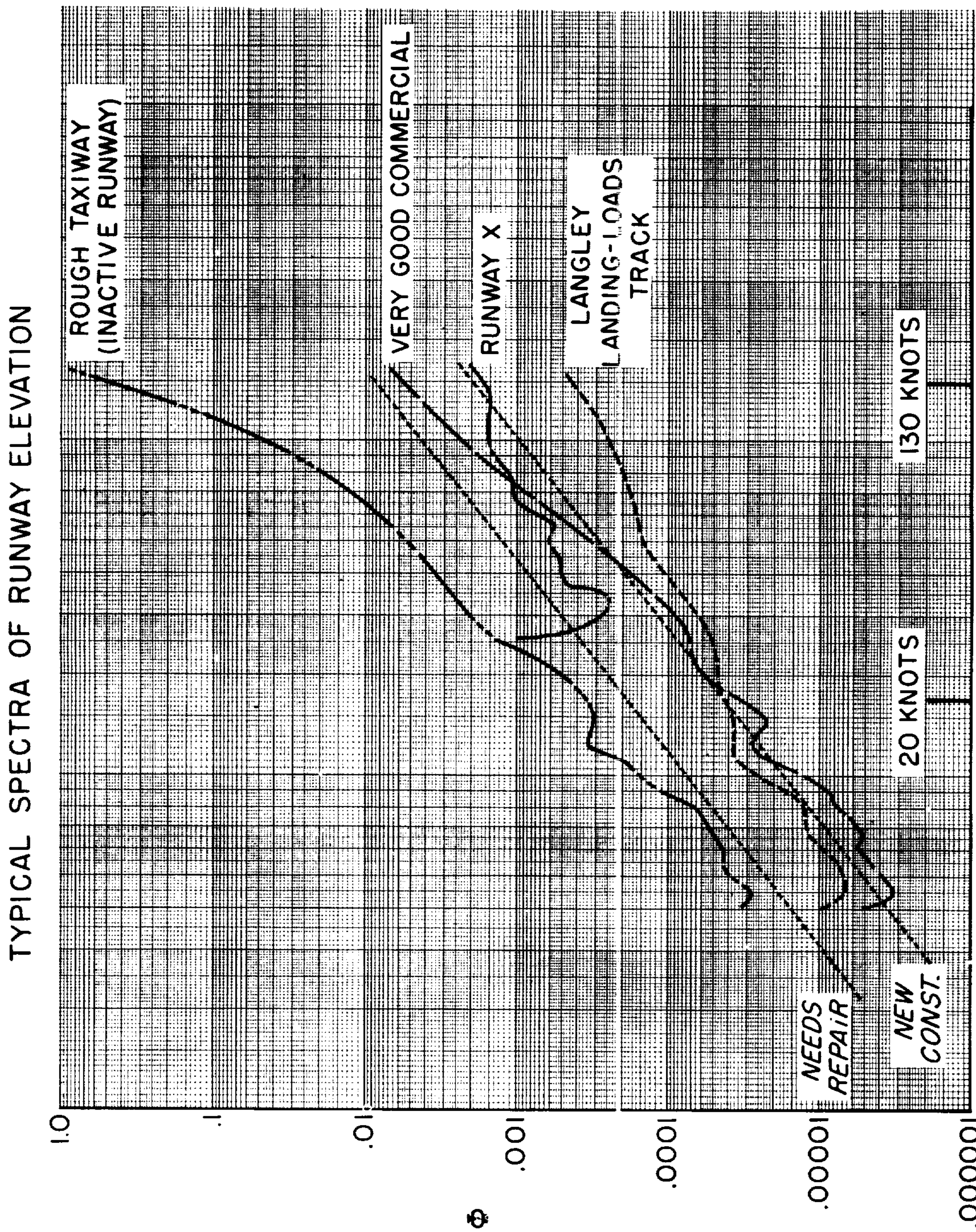

AVERAGE ROUGHNESS AMPLITUDE
l
σ'
σ'
l = 17
80
150 FT
NEW CONSTRUCTION
5/32 IN.
9/32 IN.
11/32 IN.
NEEDS REPAIR
5/16 IN.
9/16 IN.
11/16 IN.
2σ'
ROUGH TAXIWAY
(INACTIVE RUNWAY)
VERY GOOD
COMMERCIAL
LANGLEY
LANDING-LOADS
TRACK
l = 17 FT
l=80 FT
l = 150 FT
AVERAGE PEAK
AMPLITUDE, σ', FT
.12
.10
.08
.06
.04
.02
0
20
40
60
80
100
120
140
160
HORIZONTAL DISTANCE, l, FT

Figure 5



TYPICAL SPECTRA OF RUNWAY ELEVATION
ROUGH TAXIWAY (INACTIVE RUNWAY)
VERY GOOD COMMERCIAL
RUNWAY X
LANGLEY LANDING-LOADS TRACK
NEEDS REPAIR
NEW CONST.
130 KNOTS
20 KNOTS
1.0
.1
.01
.001
.0001
.00001
.000001
Φ
1
10
100
1,000
WAVE LENGTH, FT

Figure 6