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**DYNAMIC LOADS DURING GROUND OPERATIONS**

**Charles K. Grimes  
Captain, USAF**

**Aircraft Laboratory**

**June 1959**

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**WRIGHT AIR DEVELOPMENT CENTER  
AIR RESEARCH AND DEVELOPMENT COMMAND  
UNITED STATES AIR FORCE  
Wright-Patterson Air Force Base, Ohio**

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**Aircraft Laboratory  
Directorate of Laboratories**

**Project 1367  
Task 13451**

**June 1959**

**WRIGHT AIR DEVELOPMENT CENTER  
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## FOREWORD

This report was prepared by the Aircraft Laboratory, Directorate of Laboratories, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. The research and development work was accomplished under Project No. 1367, "Structural Design Criteria," Task No. 13451, "Development of Design Criteria for Dynamic Loads Induced by Ground Operations." Research was started in May 1954 and is continuing. Carl L. Preuss, Captain, USAF, of the Dynamics Branch, Aircraft Laboratory is Task Engineer.

## ABSTRACT

The status of investigations relative to determination of dynamic loads in flexible airframes during operation over rough runways and taxiways is reviewed. Recommendations for future effort which will provide a definitized runway or taxiway forcing function and dynamic load design criteria for this condition are made.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

*R. D. Keator*  
for RANDALL D. KEATOR  
Colonel, USAF  
Chief, Aircraft Laboratory

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## DYNAMIC LOADS DURING GROUND OPERATIONS

1. Nature of the Problem - The United States Air Force has been interested in the problem of runway roughness effects on taxiing aircraft since late 1952. The initial problems were concerned with wing root skin failures on F-84 aircraft operating off perforated steel pavement surfaces in Korea. Also, there were failures in the landing gear shock struts of B-47 aircraft, occurring in the Spring of 1953, which were attributed to a porpoising type response exhibited by the aircraft. Subsequent to that time there have been numerous requests for deviations from the existing airframe design criteria for this condition. In particular, aircraft such as the KC-135, F-104 and C-130 have been involved in these deviation requests.

a. Roughness Definition - The types of runway roughness in which we are specifically interested are as defined by Figure 1. The displaced slabs, tilted panels and surface undulations indicated are roughness features perhaps caused by application of inadequate smoothness standards; roughness due to deterioration with use; or roughness caused by climatic effects, for example, heaving induced by frost effects.

b. Effects on the Airframe - We have drawn a very simple dynamic model of a rigid airplane in Figure 2.  $M_1$  represents the rigid airplane mass.  $M_2$  is the mass of the tire.  $K_1$  and  $K_2$  are spring constants associated with the oleo strut and tire, respectively. This simple dynamic model will respond when subjected to an input such as exemplified by the runway or taxiway profile drawn in this sketch. There are several loading effects on the airframe, and these are outlined in the following paragraphs.

(1) Maximum Level Loads - We show in Figure 3 the relationship between the acceleration of the rigid airplane mass and taxi speed. It can be easily shown that there is a relationship between the inertia loads existing throughout the airframe structure and this acceleration. This information is required to enable designers to provide adequate structural strength for this condition.

(2) Fatigue Loads - Consider the typical time history of load as indicated in Figure 4. One way of generating fatigue load information is to count the number of times loads exceeding certain specified magnitudes are experienced. This approach results in curves of load exceedances per unit of time as shown in Figure 5. This type of information is required in generating fatigue test spectra and loads or stress information for conducting fatigue analyses.

(3) Equipment Malfunctions - There have been undocumented reports of difficulties experienced by pilots in reading their instruments because of very high frequency vibrations experienced during the take-off and landing roll-out conditions. There have also been miscellaneous undocumented reports of electronics failures caused by this same type of response.

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(4) Controllability Effects - There have been reports from B-52 pilots concerning the near inability to control the aircraft at speeds near take off velocities because of excessive control column oscillation. This again is a situation which has not been completely documented.

(5) Rigid Body Responses - Figure 6 shows a simplified dynamical system for an aircraft equipped with bicycle landing gear. Such systems are subject to a porpoising response composed of pitch and vertical translation motions combined. The WADC ran quite an extensive test program in early 1953 exploring the effects of this porpoising mode of the B-47 aircraft. It was determined that the airframe and gear loads were well within design values although the root mean square landing gear loads were increased by about 25 percent because of this porpoising response. In other words the static plus dynamic landing gear loads were 1.25 times the static vertical loads.

c. State-of-the-Art Airframe Design

(1) Bulletin ANC-2 Versus Obstacle Testing - The horizontal line in Figure 7 presents the load factor applied to the distributed dead weight items of current aircraft. This is the Bulletin ANC-2 Taxi Design Condition. We know from analysis as well as from obstacle test results that the distributed load factor or acceleration is as indicated by the broken curve in Figure 7. The obvious question which arises then is are we under designing certain portions and over designing certain other portions of our aircraft wing structures?

(2) Obstacle Test Philosophy - There is really very little that can be said about the rationality of obstacle tests. There have been limited attempts made to relate the heights and lengths of obstacles used in these tests to the actual profile characteristics as determined by profile surveys. These have not actually been too successful. More correct is the statement that these kinds of tests are established arbitrarily. However, on the basis of past experience it has been determined that obstacles of height 4 to 4 1/2 inches with lengths varying from 1 foot to approximately 20 feet are satisfactory and the aircraft is satisfactory if it exhibits the capability to traverse same. The velocities of traverse include those from zero to lift off speed.

2. Load Determination Methods - There are actually two very well defined methods for computing the loads in aircraft structures during ground operations. We shall discuss these very briefly.

a. Analog Computation Methods - We have indicated in Figure 8 the approach utilized in this method. An actual profile of a runway or taxiway surface is played into a direct analog of the airframe. This procedure allows us to read out explicitly time histories of such quantities as c.g. acceleration, wing bending moment, nacelle accelerations, wing tip accelerations and other information which may be desired. The response time history may then be operated upon to yield maximum level loads versus taxi speeds for design purposes and load exceedances per unit time versus load curves for use in fatigue analyses and tests.

b. Generalized Harmonic Analysis - This method is somewhat more sophisticated than the analog method outlined above. It is depicted by Figure 9. Very briefly, a profile is read into a computer which has been programmed to compute a function referred to as the power spectral density. This power spectral density (PSD) roughly exhibits the capability of the runway or taxiway to excite certain frequencies which are inherent in the flexible airframe. The next step in this process consists of computing an airplane transfer function to relate input to output PSD. This computation may be effected by use of desk calculators, analog computers or digital computers and requires that we know certain vibration characteristics of the airplane and the landing gear characteristics. A very simple mathematical combination of the input PSD and the airplane transfer function yields an output PSD function. This output PSD function can then be operated upon to yield maximum loads for design and fatigue loads information of the type which we obtain from the analog approach.

c. Computational Methods Discussion

(1) Analog Method - This method contains certain inherent advantages. In particular, it is simple and direct in principle. It also allows inclusion of the non-linear characteristics of the landing gear oleo. With respect to disadvantages, the method is less accurate than digital computation techniques and it is also difficult to classify the severity of the runway or taxiway input to the airframe. Also, the processes involved in developing the runway or taxiway analog are complex and not too easily applied.

(2) Generalized Harmonic Analyses - The advantages of application of this technique are several. For example, concise forcing functions or PSD's are provided which allow easy classification of roughness intensity. It develops that the area underneath this PSD curve or mean-square value is directly proportional to the roughness intensity. This method also allows more easy assessment of airframe mass and elastic data changes on the airframe response. These changes quite often occur because of airplane growth. The disadvantages to this approach are that it requires a linear airframe-landing gear system and also requires that taxi velocity be constant.

3. Profile Survey Methods - It should be apparent at this time that in order to adequately determine the loads, either maximum level or fatigue loads which are experienced by flexible airframe structures, the actual characteristics of runway and taxiway profiles must be determined. In this connection there are several means by which profile surveys can be made. A brief review of these methods is considered in order.

a. Seismic Instruments (Roughness RMS) - Figure 10 shows the characteristic frequency response curve associated with a seismic instrument. It has been determined that the natural frequency of such an instrument must be much, much less than one cycle per second to obtain the desired amplitude ratio for accurate recording, that is, if reasonable profile recording velocities are to be obtained.

b. Manual Surveys - The surveys referenced here are those conducted by means of conventional surveying instruments, that is by use of a rod, tape and transit. This approach is very laborious and requires approximately 6 hours for 3 men to measure and record 700 data points. It is considered that some more rapid means for making profile surveys is desired and required if periodic surveys of runways and taxiways are to be made.

c. Automatic Profile Surveying Equipment - The profile recording system being developed by Wright Air Development Center is illustrated in Figure 11. Basically this system uses a horizontal light beam as a reference from which profile height measurements are made. The profile height is measured and recorded every 6 inches of horizontal distance. This record will be made on paper tape which is subsequently to be played into an 1103A digital computer. This computer will be programmed to read out both runway profile heights and runway power spectral density functions. These PSD functions, as previously mentioned, will provide for display of amplitude-frequency information. The WADC system is currently undergoing modification and it is estimated that it will be available for use by approximately 15 January 1960.

4. Runway Profile Data Availability - Most of the data currently available has been collected by means of rod, tape and transit surveys.

a. United States - Data have been obtained for a runway and taxiway at the Lockheed Air Terminal. One runway at Boeing-Seattle Airport has been surveyed and the NASA has made surveys at five commercial airports in the eastern part of the United States.

b. NATO Countries - Thirty-four runways have been surveyed under cognizance of the Advisory Group for Aeronautical Research and Development (AGARD) under NATO. No taxiways have been recorded. The recorded runway profile data have been tabulated and PSD computations made by the NASA. These profile data and PSD functions are published in NACA Technical Note 4303. The NATO surveys include one runway which has been surveyed periodically over a period of several months to explore the effects of climatic changes. Figure 11 shows the differences in root-mean-square value as determined from February and August surveys. Note that the difference in root-mean-square value which was previously mentioned as indicative of roughness intensity varies approximately .01 foot or 0.12 inches. This variation is approximately equivalent to the allowable profile height deviation stipulated in Air Force Regulation 86-5 and 5A as we can see on the next chart, Figure 12.

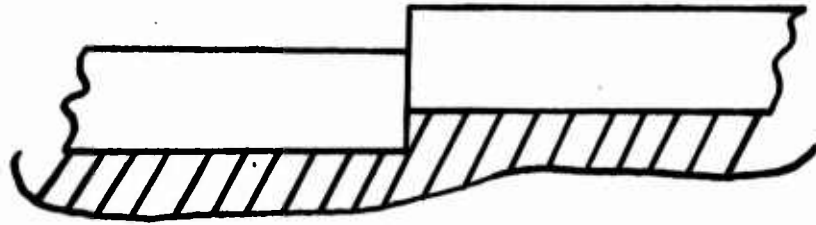
5. Construction Standards (Smoothness) - Current USAF smoothness standards are as exemplified in the top sketch of Figure 13. Note that the allowable deviation is 1/8 of an inch in a 10 foot radius and that this deviation corresponds to the change in root-mean-square value as caused by climatic effects previously mentioned for this particular NATO runway. The bottom portion of Figure 13 illustrates the smoothness standards recommended by

NASA on the basis of some of their most recent studies. The maximum allowable deviations with their associated wave lengths  $L$  have been determined based on consideration of the taxi speed range of 20 to 130 knots and assumes the primary response of the aircraft at  $1\frac{1}{2}$  to 2 cycles per second. This appears to be a reasonable assumption based on existing airplane response information.

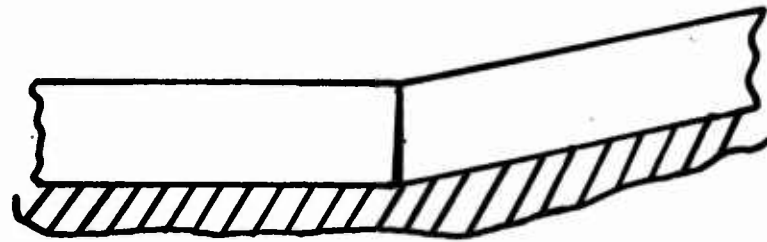
## 6. Recommended Future Action

- a. Develop the WADC Profilometer - This recommendation is apparent since without such an instrument capable of rapid recording of runway profiles the problem of determining the effects of climatic changes and of defining runway roughness inputs will be very difficult and time consuming. This development is underway as stated and will be continued.
- b. Definitize Runway and Taxiway Input Functions - A comprehensive survey of USAF air base runway and taxiway surfaces is recommended in order to provide the required definitization of runway and taxiway characteristics.
- c. Establish Smoothness Standards - It is believed that the establishment of runway and taxiway smoothness standards will require the participation of NASA, USAF Air Installations, U.S. Army Corps of Engineers and the WADC. In addition it will be necessary to consider the USAF mission in establishing smoothness standards and in particular the fact that certain USAF operations will not permit the time and expense required to develop surfaces meeting very highly developed or sophisticated smoothness standards.
- d. Develop Load Computation Methods - It should be apparent at this stage that without adequate means for determining the responses of flexible airframe structures and the loads resulting from this response, definitization of runway roughness is rather pointless. It is, therefore, recommended that current efforts of the NASA and WADC be continued and expanded as necessary.
- e. Establish Airframe Design Criteria - This recommendation actually cannot be effected until all of the other recommendations have been completed. It is considered that such criteria will consist of a representative runway or taxiway input function being defined plus a means of computing the airframe response thereto. In addition the criteria should indicate how one selects the maximum load levels for use in initial design of airframe structures as well as the means for selecting fatigue load levels for test and/or analysis purposes.

*Displaced Slab*



*Tilted Panel*



*Surface Undulations*

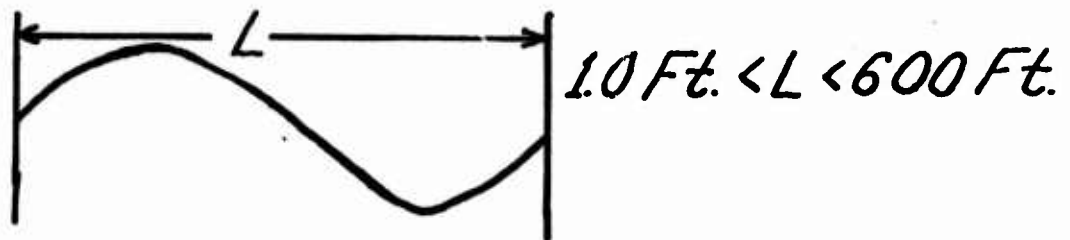


Fig.1 Definition of Runway Roughness

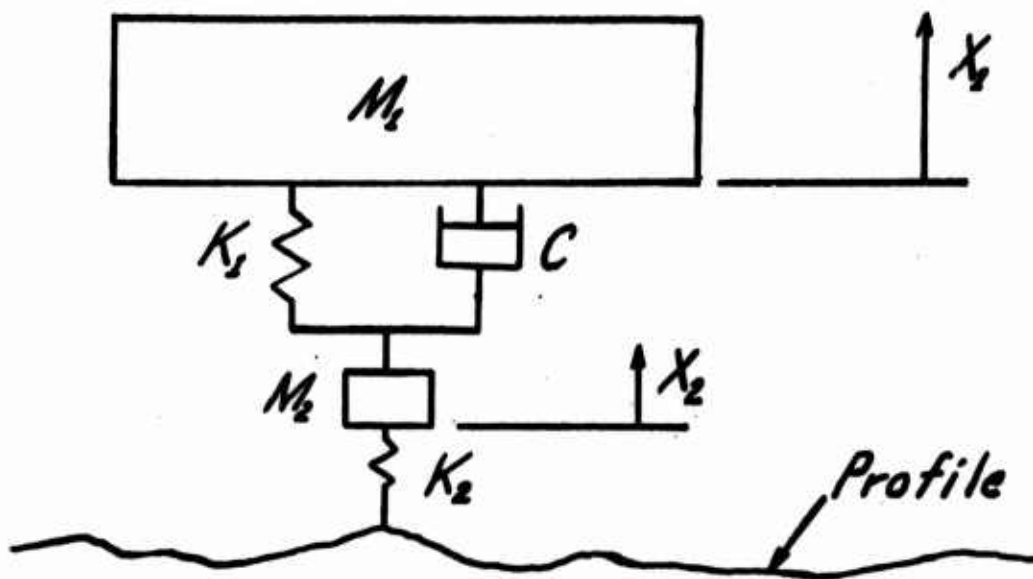


Fig. 2 Simple Dynamic Model

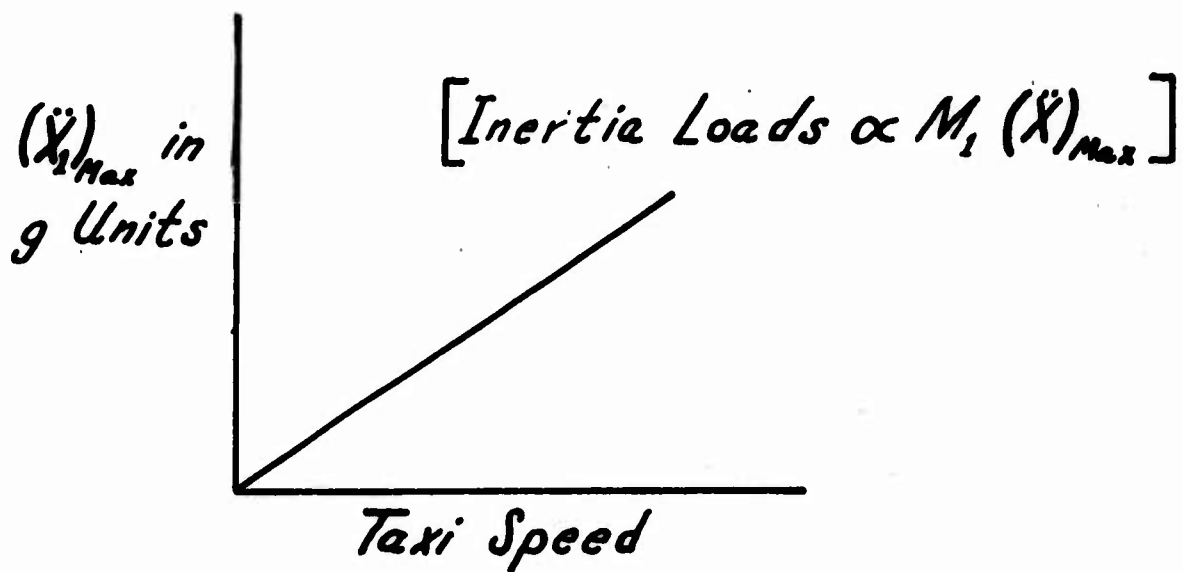


Fig. 3 C. G. Acceleration vs. Taxi Speed

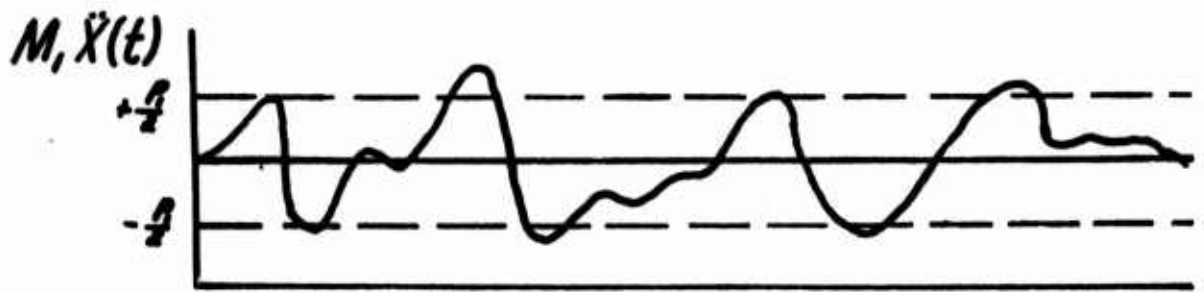


Fig. 4 Load-Time History Time

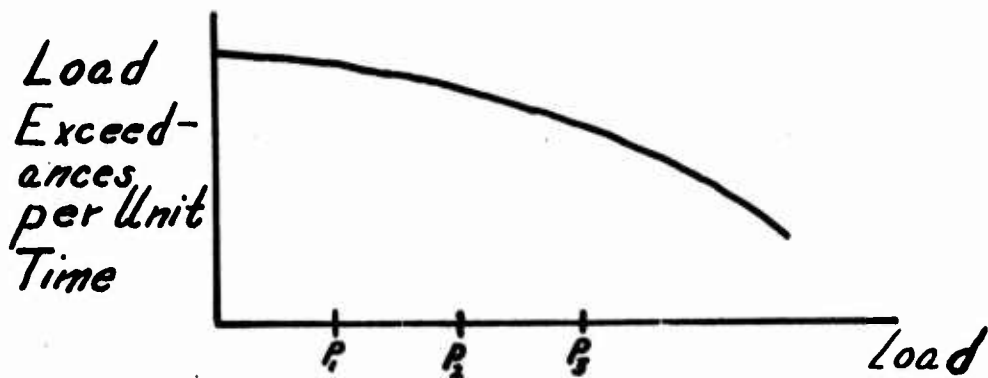


Fig. 5 Load Exceedances vs. Load

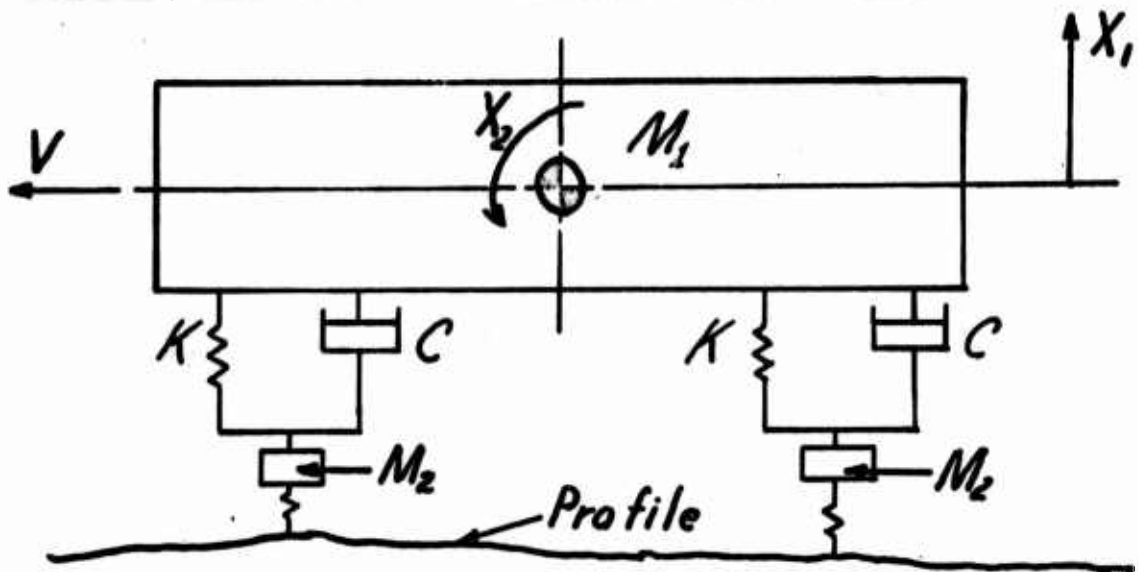


Fig. 6 Dynamical Model-Bicycle Landing Gear

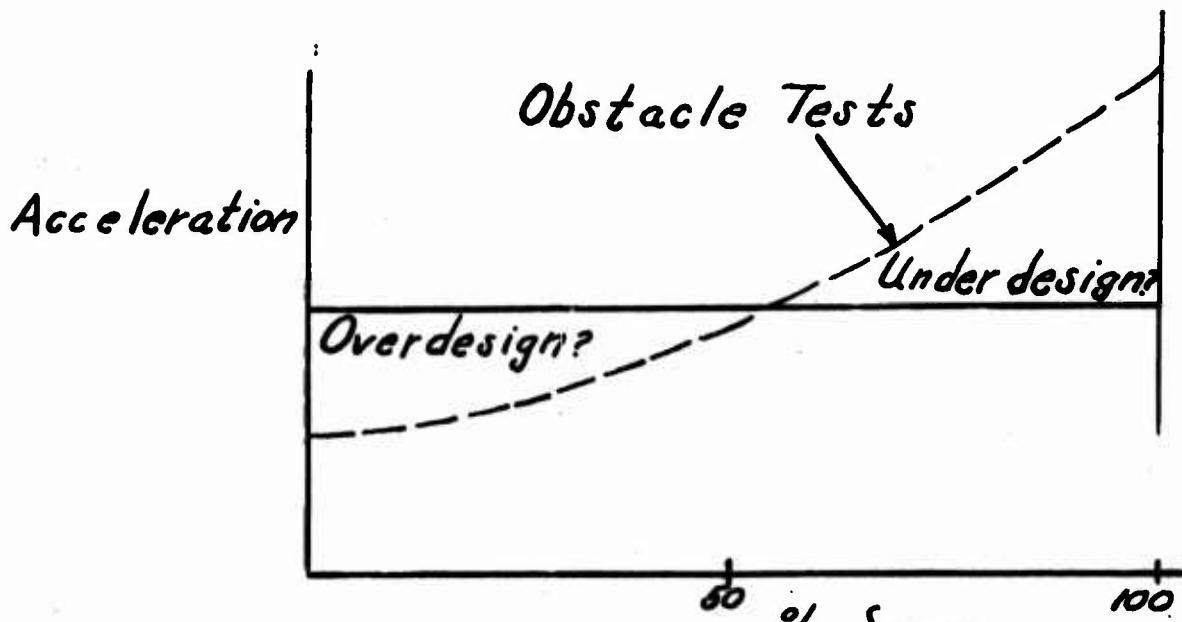


Fig. 7 Bulletin ANC-2 vs. Obstacle Tests

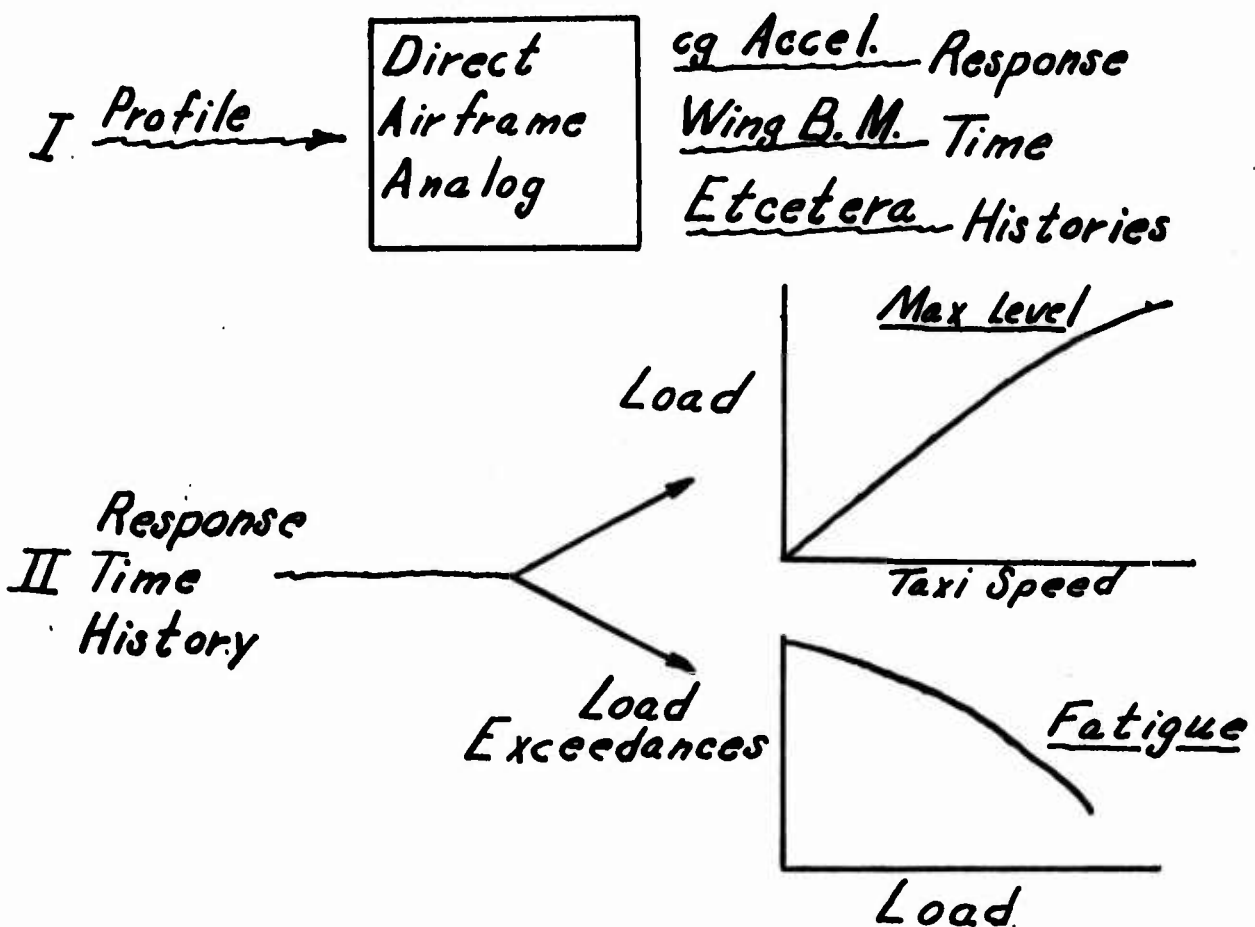


Fig. 8 Analog Load Computation

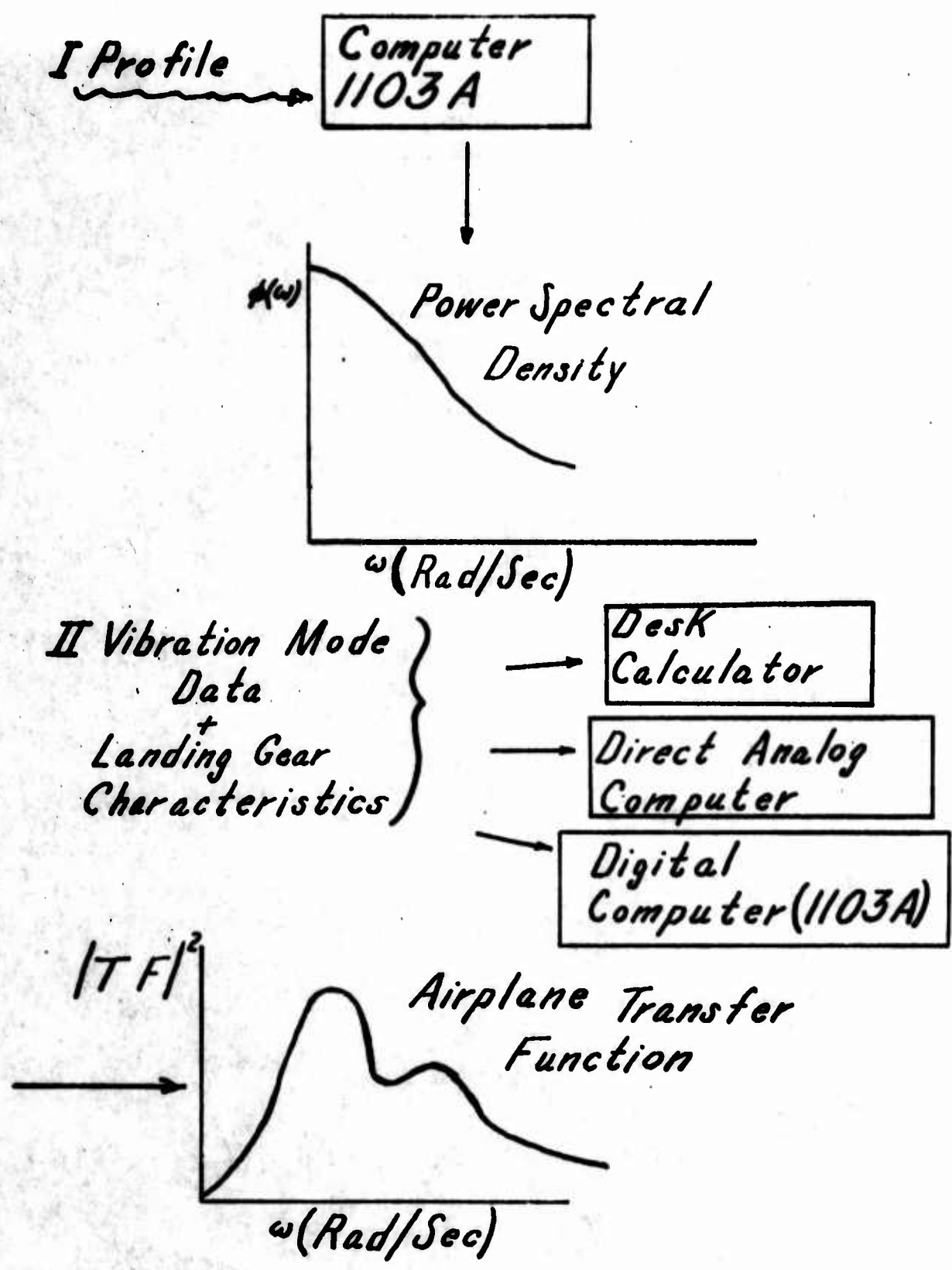
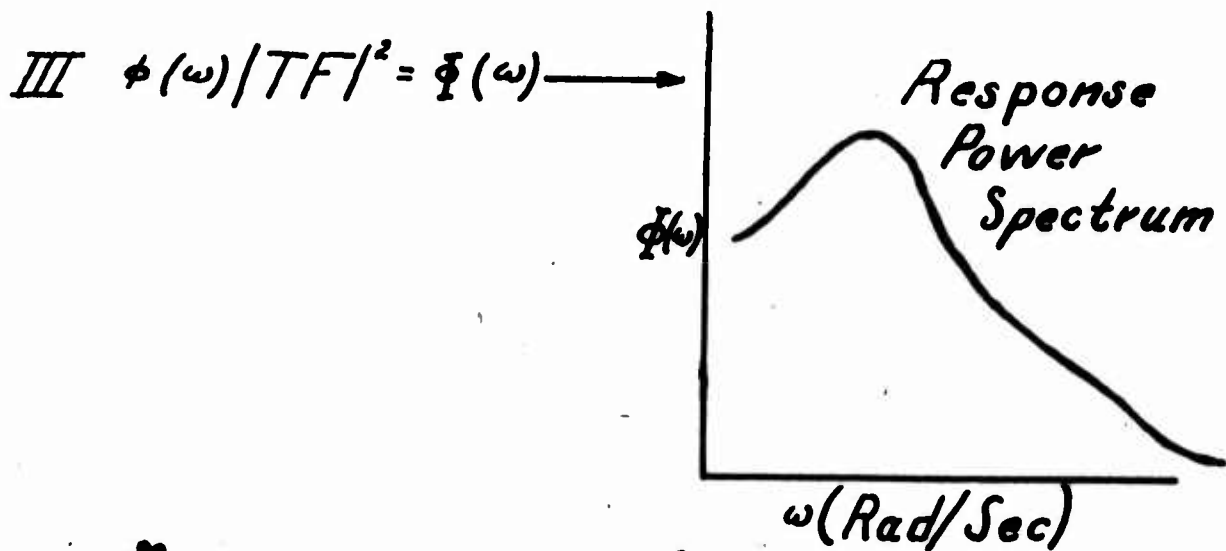


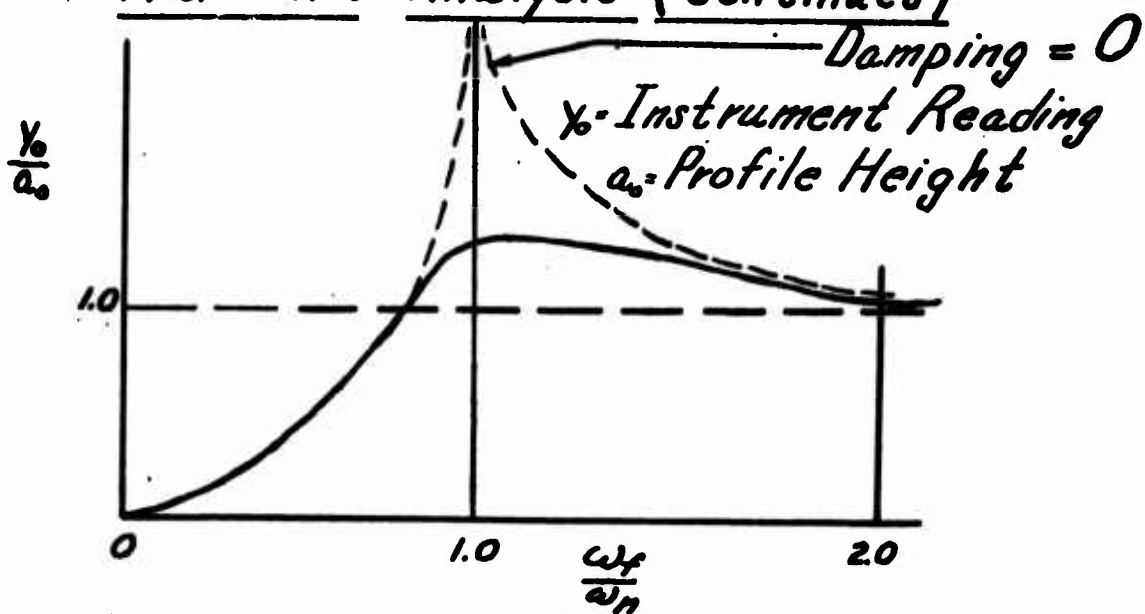
Fig. 9 Load Computation by Generalized Harmonic Analysis



IV  $\int_0^{\infty} \Phi(\omega) d\omega = \sigma^2 = (RMS)^2 \rightarrow$  Max Loads

$\int_0^{\infty} \omega^2 \Phi(\omega) d\omega$  and  $\sigma \rightarrow$  Fatigue Loads

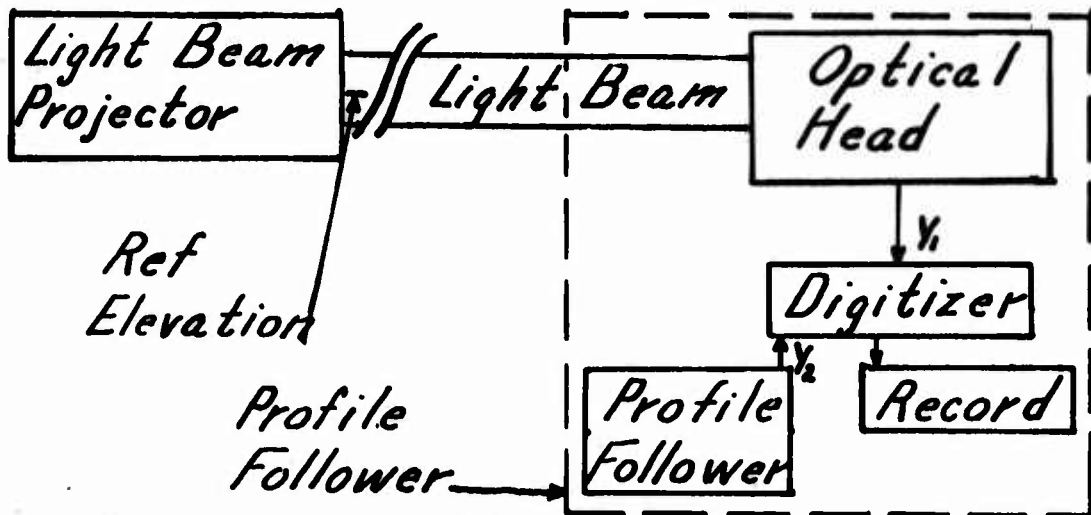
Fig. 9 Load Computation by Generalized Harmonic Analysis (Continued)



$y/a = 1.0$  Desirable - Requires  $\omega_n \ll 1.0$  CPS

Fig. 10 Frequency Response - Seismic Instrument

WADC Profilometer System:



Profile Height =  $y_1 + y_2$

Computing:

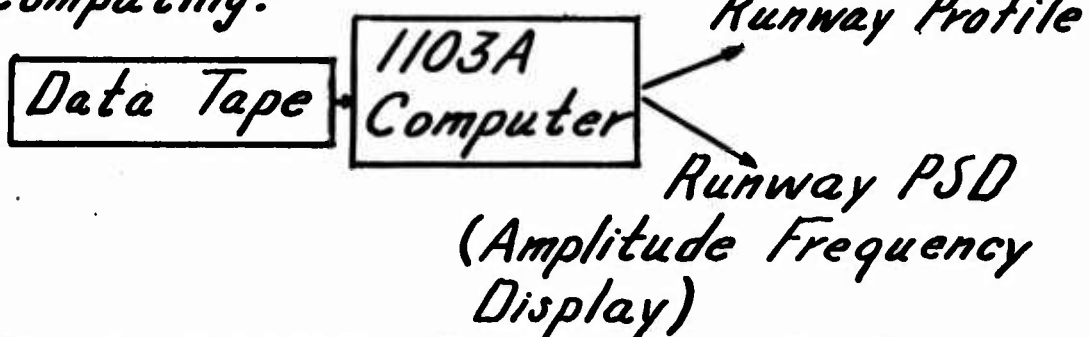


Fig. 11 WADC Profilometer System

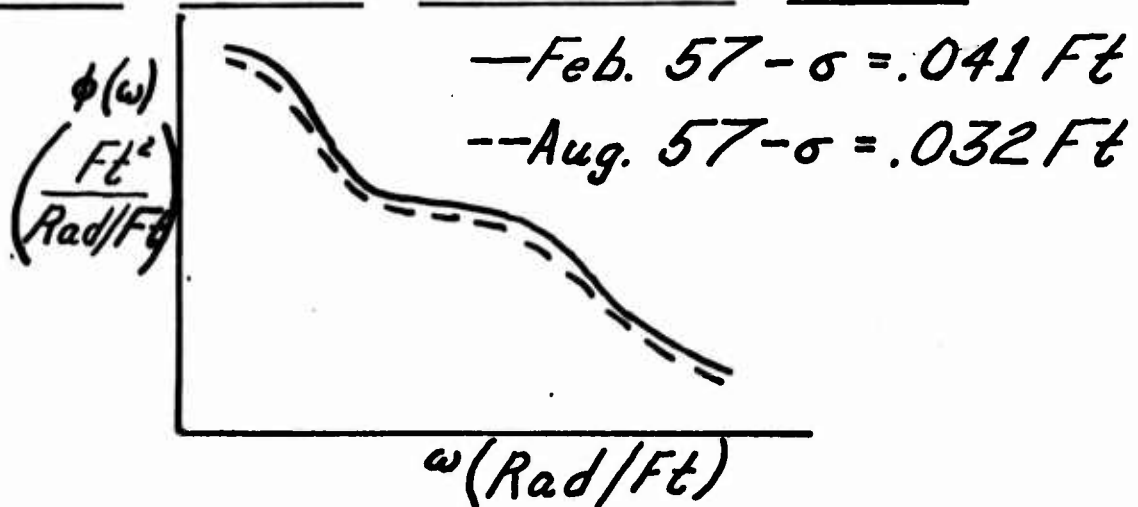
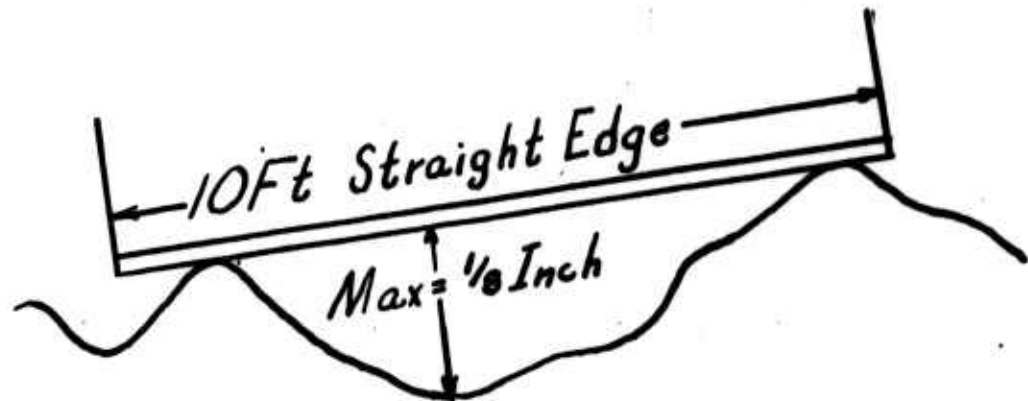


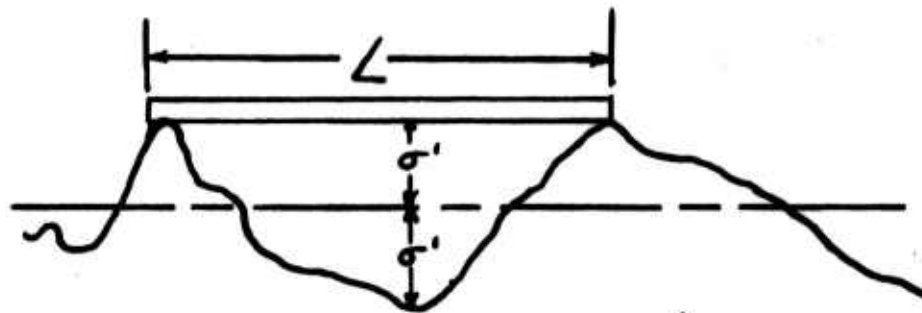
Fig. 12 Climatic Effects on Roughness

USAF (Current)

AFR 86-5 and 86-5a



NASA (Recommended)



$L$	26'
17Ft	5/32 Inch
80Ft	9/32 Inch
150Ft	11/32 Inch

Based on 20-130 Knot Taxi Speeds  
Assuming Primary Response at 1.5-  
2.0 CPS

Fig. 13 Smoothness Standards