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PRELIMINARY STUDY OF INPHASE GUSTS AND MOMENT FORCE WIND LOADS OVER THE FIRST 150 METERS AT KSC, FLORIDA

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May 1985

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16. ABSTRACT

Initial results have been completed on a mathematical/statistical analysis of inphase gusts and wind velocity moment forces over the first 150 m at the Kennedy Space Center, Florida. The wind velocity profile data used in the analysis were acquired at the KSC 150 m Ground Wind Tower. The results show that planetary boundary layer (PBL) winds can sustain near-peak speeds for periods up to 60 sec and longer. This is proven from calculating the auto-correlation functions of moment forces for several 10-min cases of wind profile data. Although this analysis is preliminary, the results prove that lower atmospheric planetary boundary layer winds do have a periodic variation for long periods of time. This flow characteristic is valuable as aerospace vehicle engineering and design criteria where wind loading must be determined. Such information is also important to the aviation and surface transportation engineers.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TECHNICAL MEMORANDUM

PRELIMINARY STUDY OF INPHASE GUSTS AND MOMENT FORCE WIND LOADS OVER THE FIRST 150 METERS AT KSC, FLORIDA

INTRODUCTION

In a previous study entitled, "Inphase Characteristics of Winds to 150-Meters," by John W. Kaufman and Kelly Hill, Atmospheric Sciences Division, NASA/Marshall Space Flight Center, Alabama 35812, May 1983, it was stated, "Although the peak wind at each anomometer level, for any time period, does not occur simultaneously over the height of 150 meters, wind speeds equal to or nearly approximating peak values can exist concurrently and can be maintained for periods of several seconds."

Wind in the Earth's boundary layer plays a significant role in the design, launch, initial flight, and landing of aerospace vehicles. Thus, a vehicle standing unprotected on-pad may experience wind speeds which are structurally critical. In addition to the structural problem, certain wind direction with high speeds could cause a vehicle to collide with its adjacent launch structure at the time of liftoff. Therefore, an effort continues to be placed on the analysis of ground wind profile data at launch and landing sites. Emphasis in this study is placed on the occurrence and duration of inphase gusts and moment forces due to winds on an assumed rigid cylinder over the first 150 m. This is referred to as the inphase characteristics of gusts and moment forces due to winds for the study of the static and dynamic response of aerospace vehicles to ground winds.

Although the results herein are preliminary, further study is continuing to refine the analysis and to investigate how such results actually affect the design, operations, launch and landing of such vehicles.

DATA ANALYSED, THE 150 M GROUND WIND TOWER AND ASSUMED CYLINDER

Wind data for this study were obtained at the 150-Meter Ground Wind Tower at the Kennedy Space Center, Florida [1]. Approximately 14 sets of wind profile data, having recording durations of 30 to 100 min, are available. These data were recorded on analog magnetic tape then digitized at a rate of 10 data points per second. Data were obtained for six anemometer levels (i.e., 18, 30, 60, 90, 120, and 150 m) (Fig. 1). Due to the favorable three-cup anemometer and wind vane systems used on the tower [2], this digital rate provided an accurate reproduction of the wind data recorded.

The data base used included wind speeds associated with thunderstorms, tropical storms, hurricanes and frontal activity; however, most of the data were recorded during typical thermally unstable afternoon periods. The data were first segmented into 10-min sample sizes of which about 10 hr of useful data were used in this study.

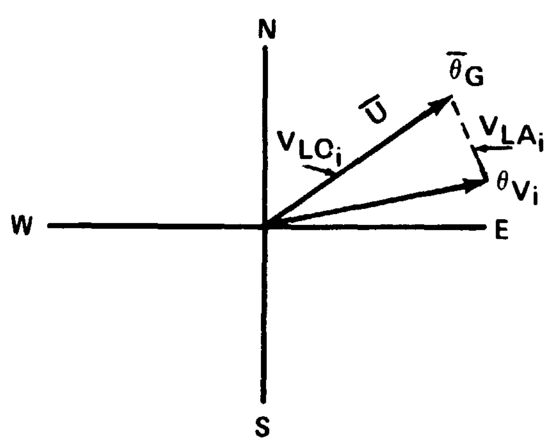
The assumed 1-m diameter rigid cylinder is also depicted on Figure 1. The cylinder is shown to be 165 m. Here the moment forces due to winds were calculated using each level of wind data over a cross-sectional area of 8, 23, 30, 30, 30 and 30 m^2 as shown on the figure. The corresponding mid-level winds were applied in the moment force expressions as shown on Figure 2. In the expressions on Figure 2 the the air density was held constant at about 1.3 kg m^{-3}, C_D was held constant at 1.0, and L_M is the moment length. Figure 3 shows how the grand mean wind speed and direction were calculated for each 10-min sample. The values were obtained as follows:

1) Each 10-min sample was analysed independently.

2) For each wind velocity in the sample the wind velocity components were calculated. This took 7200 calculations (Fig. 3). The average of the components was then obtained and vectorially added to calculate the grand mean wind speed and direction.

3) The grand mean wind direction was then used to represent the longitudinal wind direction and the direction normal to this is, of course, the lateral direction.

4) All 7200 wind velocities, for all six anemometer levels, were then reflected onto the grand mean wind direction to obtain 7200 longitudinal wind velocities. The lateral (normal) velocities were computed using the sine of the angle between each of the individual velocity wind directions and the grand mean wind direction times the magnitude of each individual wind speed as shown below.



5) The 7200 longitudinal and 7200 lateral velocities, in each 10-min sample, were then used to compute the moment forces by using the expressions shown on Figure 2.

6) However, prior to 5) above the raw wind velocity data were smoothed by an 11-point weighted filter function derived from the normal curve

$$Q(t) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-t^2/2\sigma^2}$$

where Q(t) are the calculated weights [3]. The weights used were 0.0005, 0.0052, 0.0297, 0.1038, 0.2197, 0.2822, 0.2197, 0.1038, 0.0297, 0.0051, and 0.0005. Such filtering was necessary to eliminate a few "wild" data points that are occasionally found in the data used for this study.

A 10-min sample of wind speed data is shown on Figure 4. These data were recorded at the 60-m level of the 150-m GWT at KSC from 16 h 30' 52" to 16 h 40' 52" GMT on October 19, 1967. Figure 5 is the power spectral density (PSD) of this wind speed sample versus frequency, F(n), as computed by the Fast Fourier Transformation (FFT). From theory [4] the frequency band is actually between n and (n + dn) or

$$F(n) \approx \varepsilon^{2/3} n^{-5/2}$$

where $\varepsilon^{2/3}$ is the rate of viscous dissipation and n is frequency.

The theoretical slope is shown on Figure 5 to compare to the actual spectral density values (scattered points) of the 10-min sample of wind speeds analysed. The theoretical slope (i.e., -5/3) compares quite well with that of the PSD versus F(n) on Figure 5.

Figure 6 shows a composite of 15 PSD fitted slopes of 10-min samples of winds as observed at the 60-m anemometer level. Here, from an observation judgement, the PSD of the composite slopes seems to be slightly less than the -5/3 slope.

Figures 7, 8 and 9 are (1) the power spectral density versus frequency of a single 10-min sample of calculated longitudinal moment force ($F_{M_{LONG_{ijk}}}$) versus frequency, (2) the composite of 15 10-min samples of longitudinal moment forces versus frequency, and (3) the composite of 15 10-min samples of the lateral moment forces versus frequency. The -5/3 slope has also been plotted from spectral theory of wind energy decay. Comments are going to be withheld on these results until further data can be analysed. One point that can be made, however, is that the moment force equations have a V^2 variable which should place more PSD energy into the lower frequencies (i.e., a greater slope than -5/3) but this is not apparent from Figures 7 through 9.

Figure 10 shows non-normalized autocorrelations of longitudinal moment forces versus time (6.3 min) calculated from 150-M Ground Wind Tower data, KSC, Florida. The dates and times that the winds were observed are shown on the figure. Of the three correlations it is important to note the inphase characteristics of the forces. In these cases it strongly indicates that the planetary boundary layer wind has a wave period of about 200 sec. Figures 11 and 12 show PBL wave periods of about 160 and 60 sec, respectively. It has not been determined, from the results completed to date, what the percent frequency of occurrence is that PBL winds have such periodic behavior. Also, further study is required to investigate the following questions: (1) How do the wind speeds and directions relate to the periodicity of PBL flow at KSC and elsewhere? (2) What effect atmospheric properties such as temperature, atmospheric pressure and pressure gradient change, humidity, gravity, surface roughness and upwind fetch conditions, etc., have on the evolution and sustention of such periodic flows? (3) What are the problems associated with the inphase wind loading on on-pad vertically standing vehicles and other structures?

Figures 13 and 14 depict comparisons of longitudinal and lateral moment forces for two analysed 10-min samples of wind profile data. As seen in Figure 14, the correlations are nearly identical; however, in several other comparisons there is a complete lack of correlation. Again, further study of such results is required.

Figure 15 is a plot of about 60 mean longitudinal moment forces versus mean wind speed observed at the 60-m level. As expected, these moment forces compare very well with the curve (solid line) calculated from the mean moment expression (Fig. 2). Additional wind velocity profile data are to be analysed for higher mean wind speed magnitudes obtained at KSC than appear on Figure 15.

From many references on planetary boundary layer (PBL) theory of winds [5 through 13], it is a well established fact that winds turn to the right with height, from the surface to about 1000 m, in the northern hemisphere (Fig. 16). As R. A. Brown [5] states: "The solution for the balance between Coriolis and viscous forces yields an aesthetically satisfying exponential spiralling velocity profile." Although many models exist that express this spiralling, some of the first work came from Ekman in 1902 [13]. Hypothesis: If the PBL winds do turn to the right with height, would this cause a greater moment force on the left side of the assumed 165 m cylinder as employed in this analysis? Figure 17 shows that the mean lateral moment forces versus mean wind speed does have greater moment forces from the left. Here, the grand mean longitudinal direction is from zero, on the ordinate of Figure 17, horizontally to the right. Accordingly, the greater lateral forces are from the left as shown by the calculated results which were fitted by the solid curve.

GENERAL DISCUSSION

The moment force expressions shown in Figure 2 are widely used in building design problems. This and other such expressions may be found in References 14 through 20. Here, a 165 m tall rigid cylinder was assumed as the structure where the drag coefficient, C_D, was held constant at 1.0. This led to the fact that the moment forces, included in this report, can be scaled up or down to make force calculations of other similar structures with different drag coefficients.

The power spectral density (PSD) of the 60-m level wind speeds and moment forces shows results that conform to those anticipated. As presented in NASA Technical Memorandum 82473, "Terrestrial Environment (Climatic) Criteria Guidelines for use in Aerospace Vehicle Development, 1982 Revision" [21], these preliminary results tend to compare quite favorably with the spectral results on ground wind. There is no intent to use these results to infer moment forces on structures; nevertheless, they do generate interest to continue this study, particularly on the inphase characteristics of winds in the lower atmosphere.

The interesting finding is the phenomenon of PLB wind flow periodicity. This regularity of wind over the first 150 m has been recognized in prior research, but it was not known that such wave patterns could sustain for periods of 2 to 3 min. Such information can be very significant to structural design engineers who place emphasis on fundamental modes of oscillation and load constraints of free standing, on-pad vehicles, especially where wind loads and structural response of vehicles and their subcomponents are very sensitive to apparent small changes in surface winds [22]. Ryan, et al., [22] completed an extensive study on the design of the Space Shuttle vehicle and its payloads regarding ground wind loads.

Improvements to this study must include the parameters of surface stress and roughness as compared to synoptic scale parameters. The Ekman spiral criteria were related briefly (Figs. 15, 16 and 17) but eventually the surface layer flow must also be analysed in comparison to geostrophic wind conditions. This would be important in the development of a method to predict synoptic weather events in relation to PBL winds to explicitly investigate wind loads on structures. This also must include the study of wind loading during extreme wind conditions.

CONCLUSIONS

Atmospheric turbulence is an extremely variable quantity. This fact is further supported by this, and other studies, that have shown that winds are fairly well correlated over an area from the surface to 150 m for a small percent of time. The availability of turbulent flow is extremely essential to understand as such information is applicable to a vast variety of atmospheric research. This research has shown that winds at times may not always be well correlated. Thus, it is becoming evident that when high magnitude winds occur for limited periods of time, such winds tend to be quite coherent over the first 150 m.

Further study of inphase gusts and the analysis of longitudinal and lateral moment forces due to winds is required. Additional refined analyses are necessary to accomplish the following: (1) to study the inphase characteristics and correlations of longitudinal, lateral and vertical components of wind; (2) to investigate how such correlations relate to surface stress and to the synoptic conditions so that periodic wave motions of winds in the planetary boundary layer may be better understood and predicted; (3) to continue to use the favorable results from this and further studies to simulate wind loading on vertically standing aerospace vehicles and other structures; (4) to incorporate such results into other research studies such as atmospheric diffusion, vehicle and aircraft design and operation, the design of structures, etc.; and, (5) to closely coordinate results with aerodynamicists who must introduce these wind criteria into the research of static and dynamic responses of vehicles and associated structures to ground winds.

RECOMMENDATIONS

In that the planetary boundary layer (PBL) winds have well defined periodicities for significant time periods and wave forms, it seems only reasonable that to properly investigate and improve prediction of large "inphase gust events" the following action be considered. In addition to measuring winds at a single point with an anemometer and direction vane, a vertically mounted cylinder should be erected and equipped with strain gages and other essential sensors to measure wind loading over the height of the cylinder to acquire real gust and moment loading data. The height and dimensions of the cylindrical wind/moment loads sensor would of course, depend on the geometry of the area in question. For example, near an aerospace vehicle launch and runway landing complex, it may be 50 m ($\sim$160 ft) to 100 m ($\sim$330 ft) in height to study extreme gust loading on aerospace vehicles during launch and landing. It seems that such measurements would be more significant to low level spacecraft operations than a single point reading of wind speeds and directions. The interpretation of such data would take some time to complete, however, it is logical that such "volume flow" wind loads data would provide more reliable information than is presently available. The use of the cylindrical wind velocity profile system could be of value at any location where the study of surface wind and especially gust loading on structures (man made or natural) is essential. The extreme winds considered are microbursts associated with convective storms, squall line winds, frontal winds, etc., as monitored on a continuous basis.

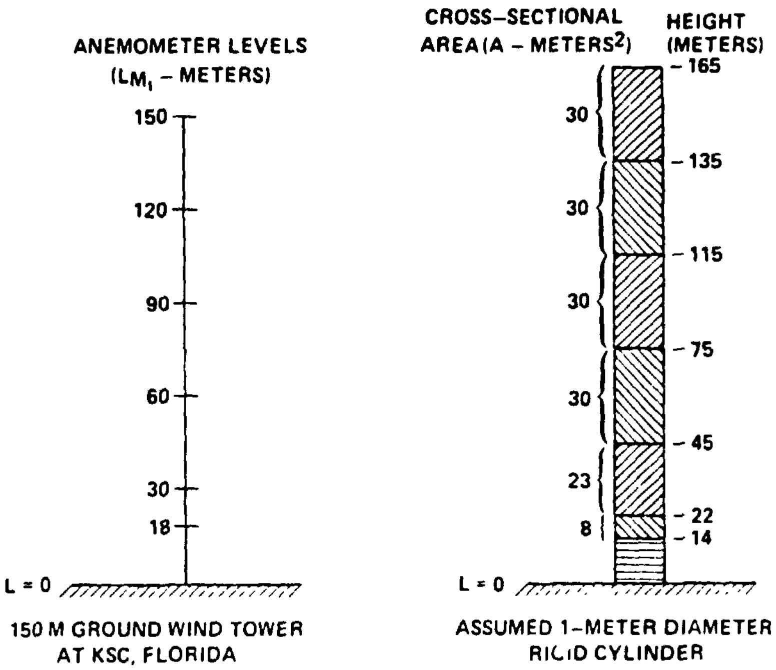


Figure 1. Ground wind tower and cylinder.

$$\Sigma F_{M_{LONG}} = \sum_{i,j,k}^{n_i, n_j, n_k} \tfrac{1}{2}\rho \; V^2_{LO_{i,j}} \; C_D \; A_k \; LM_i$$

$$\Sigma F_{M_{LAT}} = \sum_{i,j,k}^{n_i, n_j, n_k} \tfrac{1}{2}\rho \; V^2_{LA_{i,j}} \; C_D \; A_k \; LM_i$$

ρ = 1.2923 Kg m^{-3}, AIR DENSITY

V_{LO}, V_{LA} = LONGITUDINAL AND LATERAL WIND VELOCITY

C_D = DRAG COEFFICIENT HELD CONSTANT AT 1.0

A_k = 8, 23, 30, 30, 30, 30 m^2

i = 1, 2, 3, ... , 6 ANEMOMETER LEVELS

LM_i = 18, 30, 60, 90, 120, 150 METERS

j = 0.5, 1.0, 1.5, 2.0, ... , 600 SECS (10–MIN SAMPLE SIZE)

Figure 2. Moment force expressions.

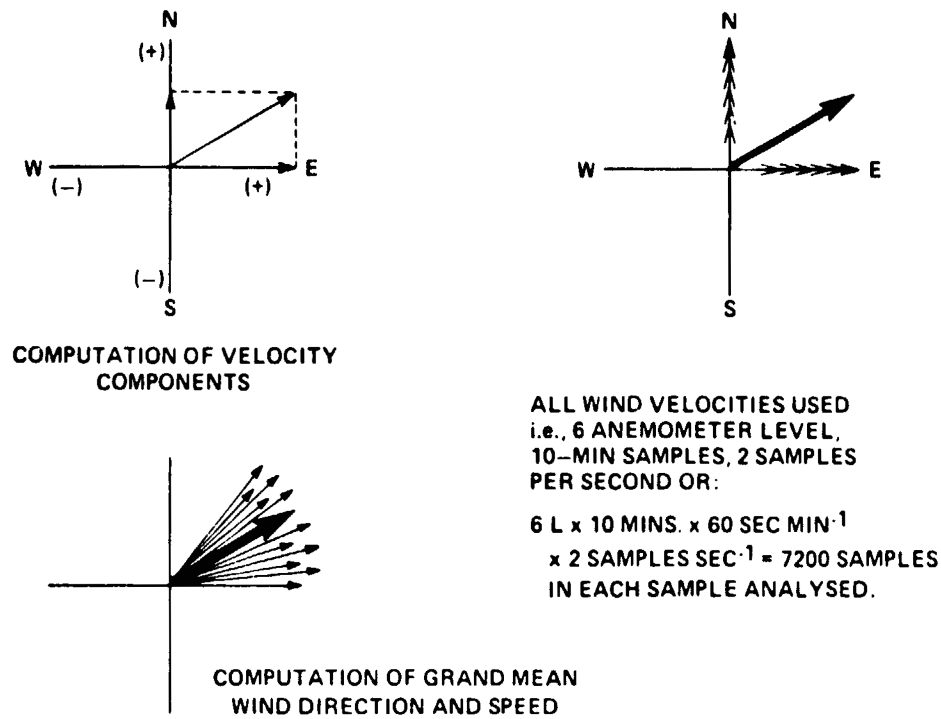


Figure 3. Computation of grand mean wind velocity, from 150 M ground wind tower data, KSC, Florida.

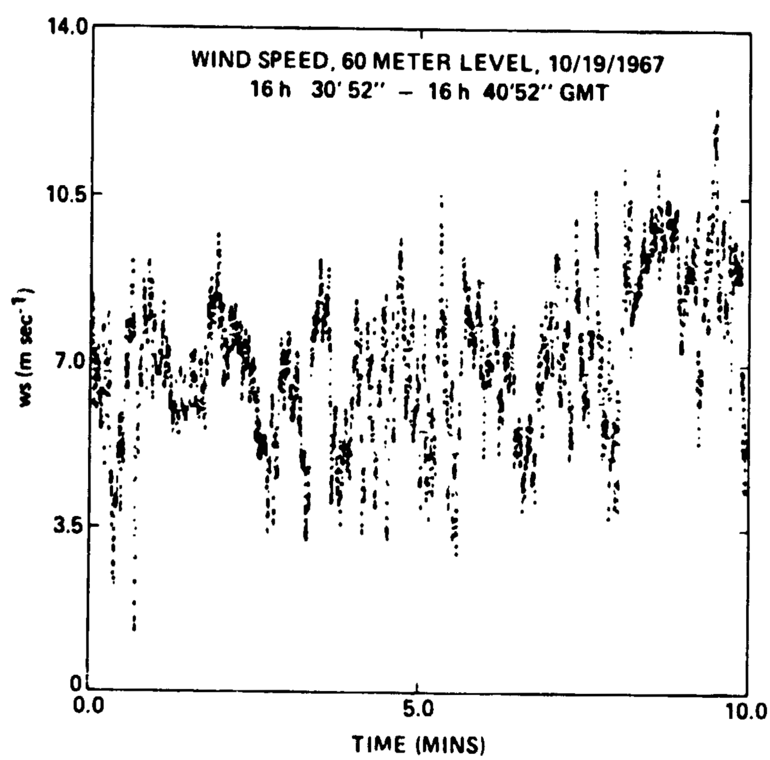


Figure 4. Wind speed versus time, from 150 m ground wind tower data, KSC, Florida.

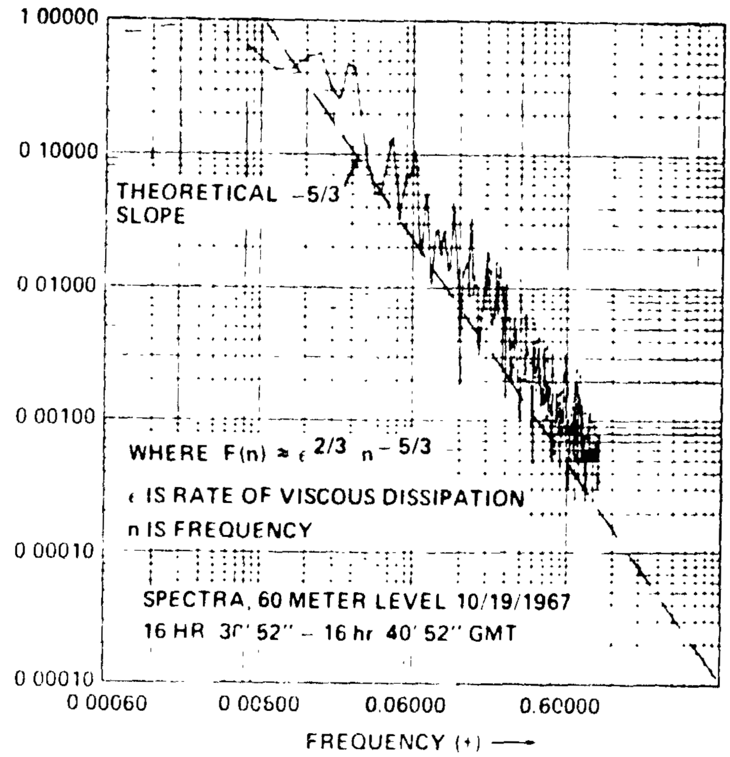


Figure 5. PSD versus frequency, 150 m ground wind tower data, KSC, Florida.

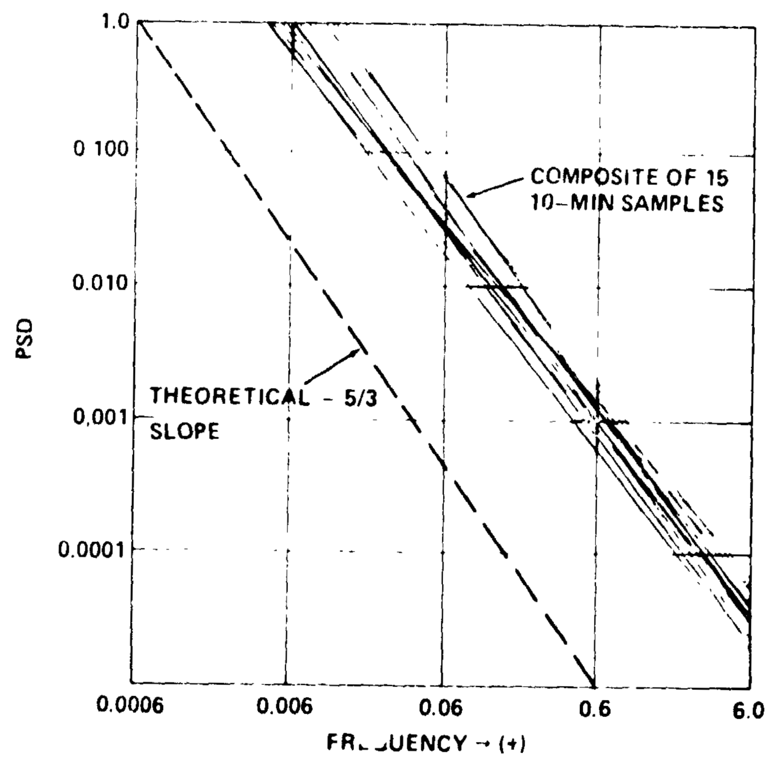


Figure 6. PSD versus frequency spectra of 60 m level winds, 150 m ground wind tower data, KSC, Florida.

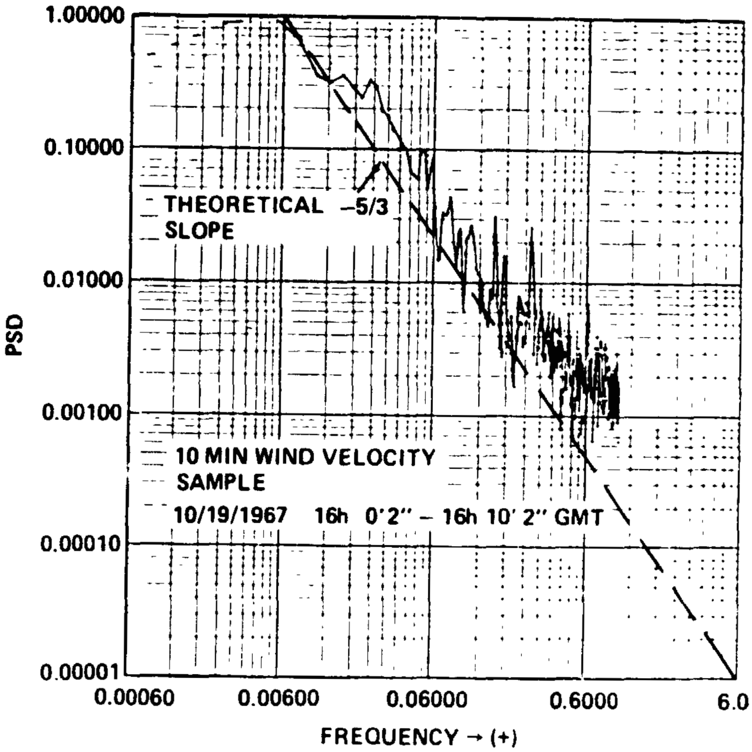


Figure 7. PSD versus frequency PSD of longitudinal moment force versus frequency, computed from 150 m ground wind tower data, KSC, Florida.

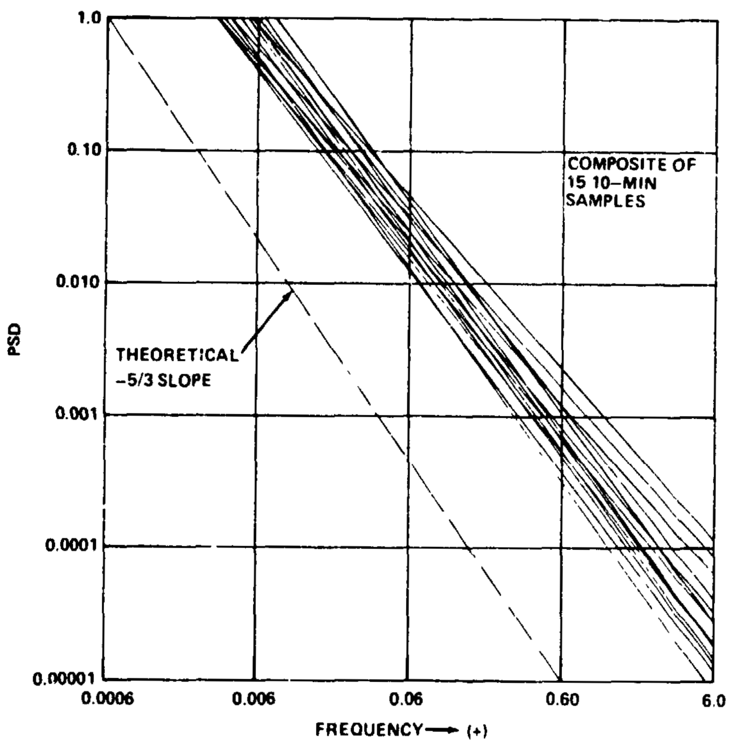


Figure 8. PSD of longitudinal moment forces versus frequency, computed from 150 m ground wind tower data, KSC, Florida.

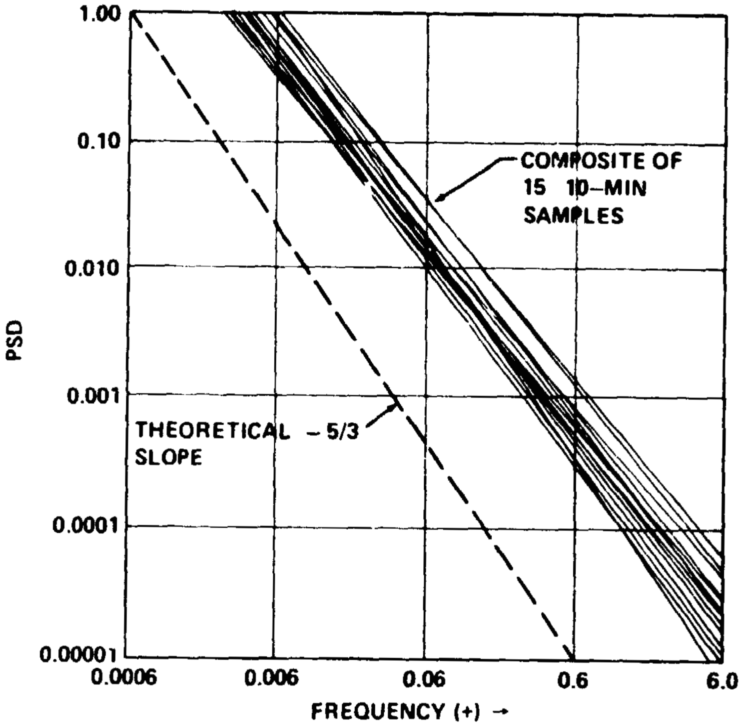


Figure 9. PSD of lateral moment forces versus frequency, computed from 150 m ground wind tower data, KSC, Florida.

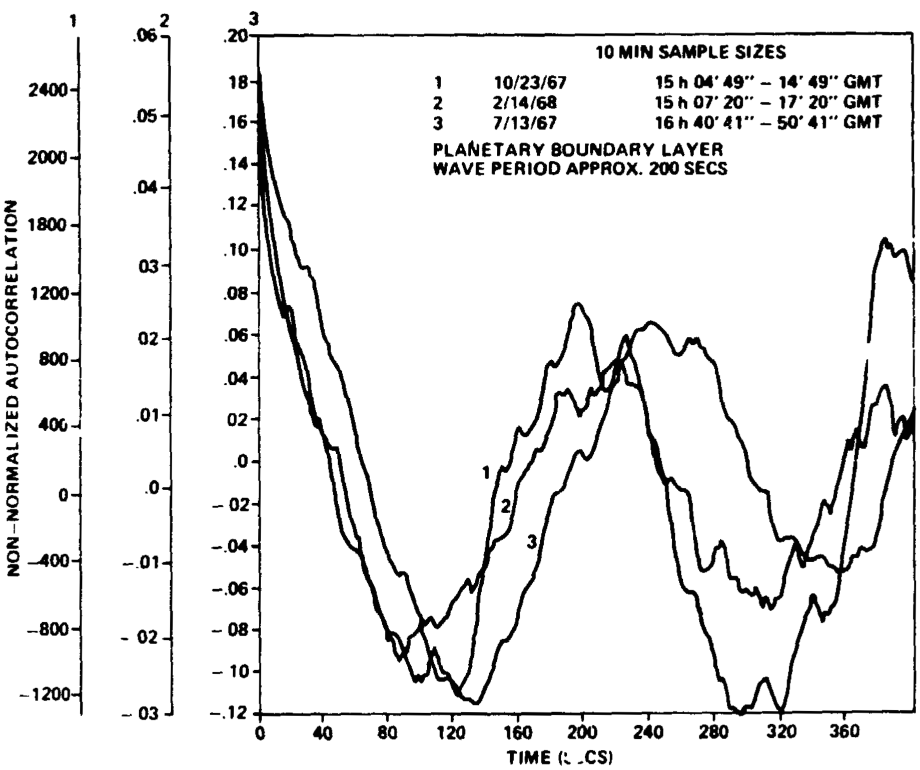


Figure 10. Autocorrelations of longitudinal moment forces versus time (6.3 min), from 150 m ground wind tower data, KSC, Florida.

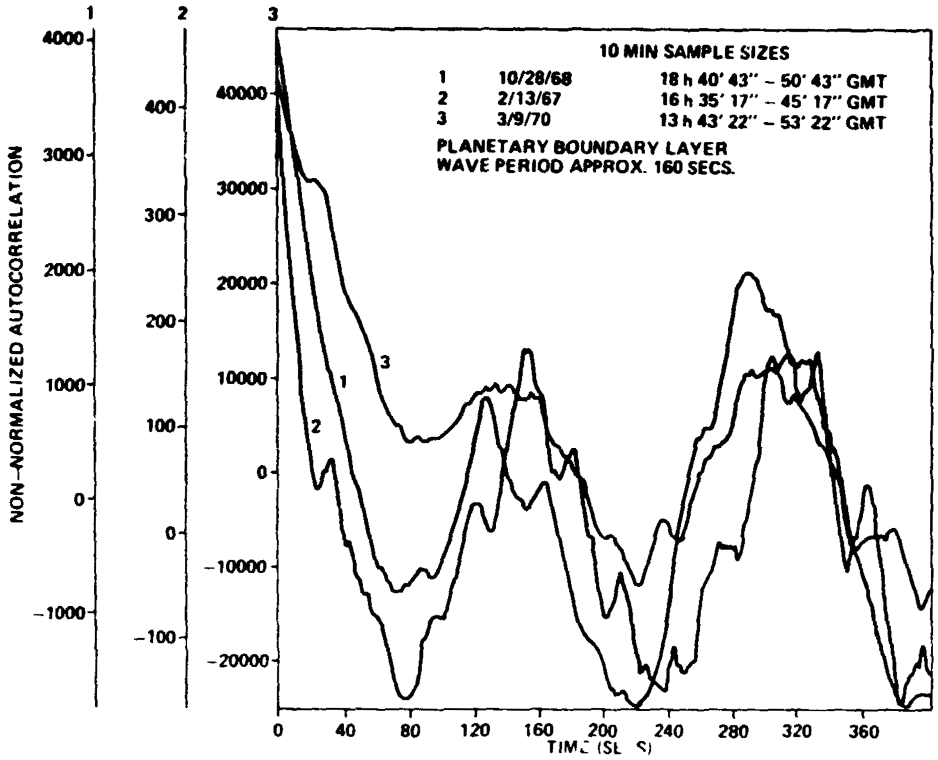


Figure 11. Autocorrelations of longutidinal moment forces versus time (6.3 min), from 150 m ground wind tower data, KSC, Florida.

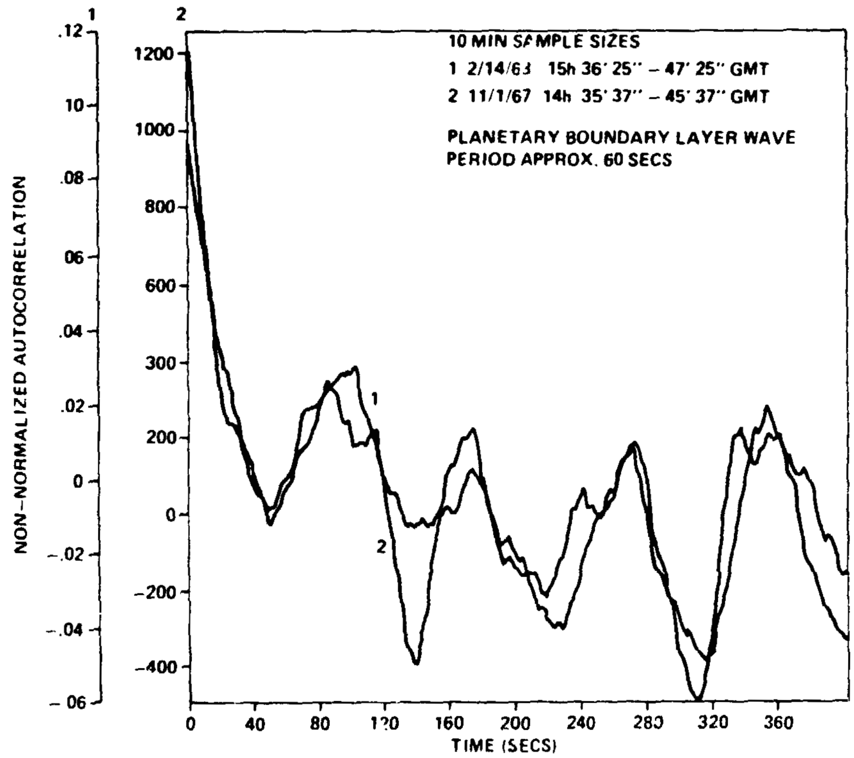


Figure 12. Autocorrelations of longitudinal moment forces versus time (6.3 min), from 150 m ground wind tower data, KSC, Florida.

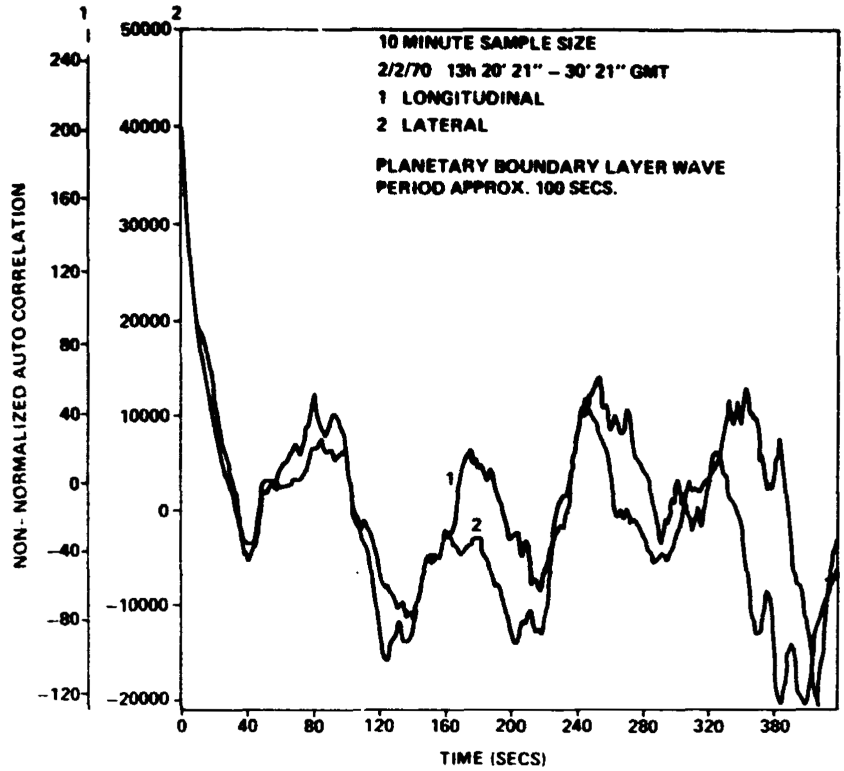


Figure 13. Comparison of longitudinal and lateral moment force correlations, from 150 m ground wind tower data, KSC, Florida.

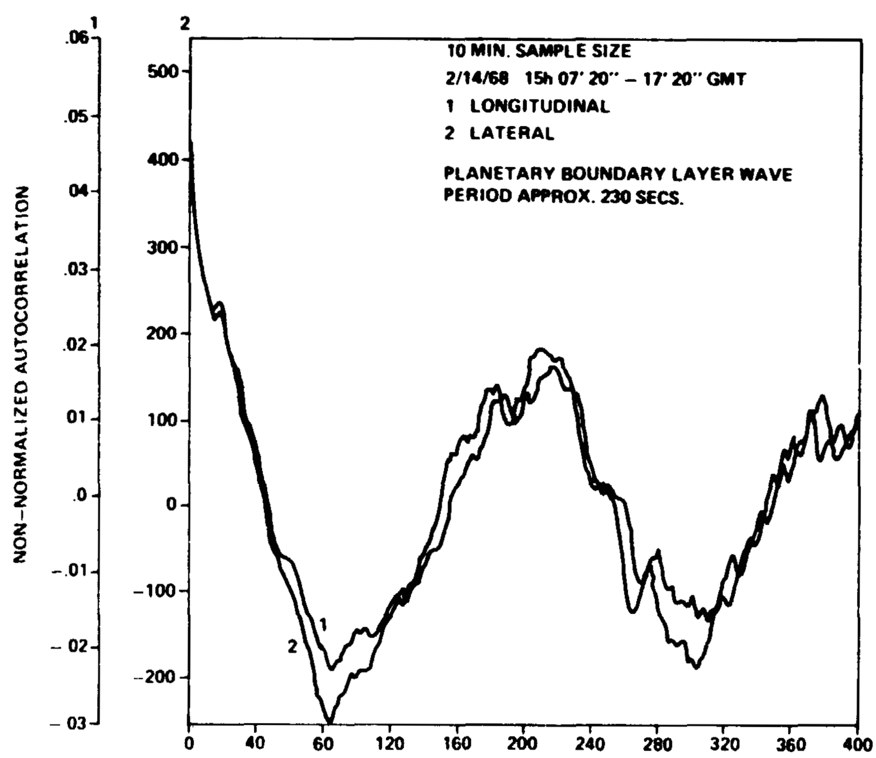


Figure 14. Comparison of longitudinal and lateral moment force correlations, from 150 m ground wind tower data, KSC, Florida.

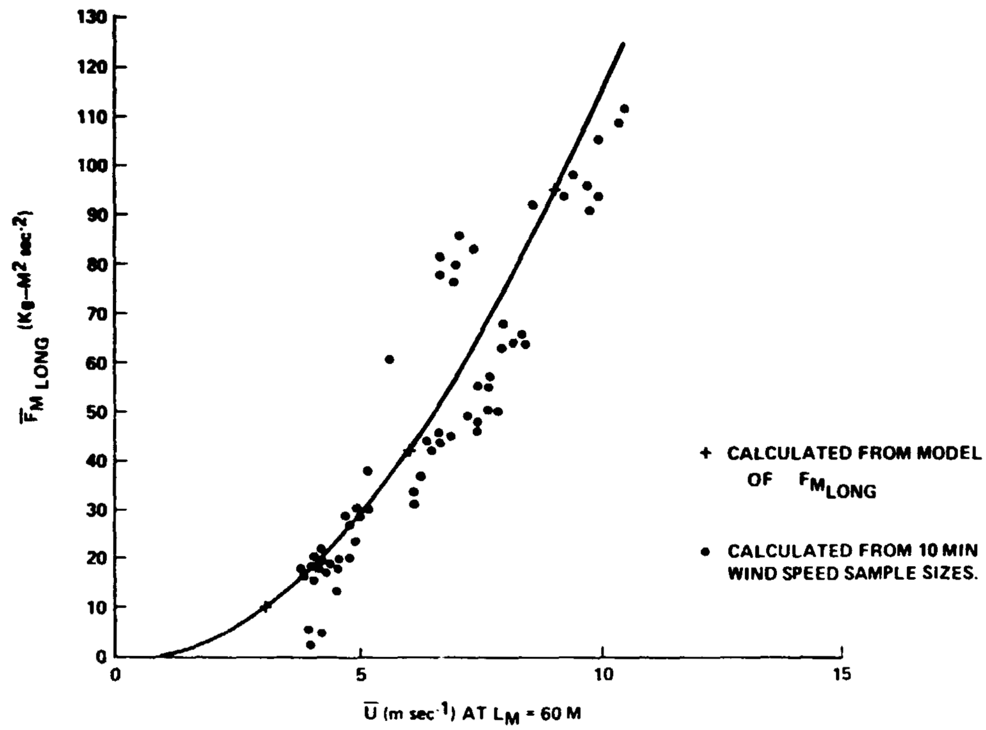


Figure 15. Mean longitudinal moment forces versus mean wind speed, from 150 m ground wind tower data, KSC, Florida.

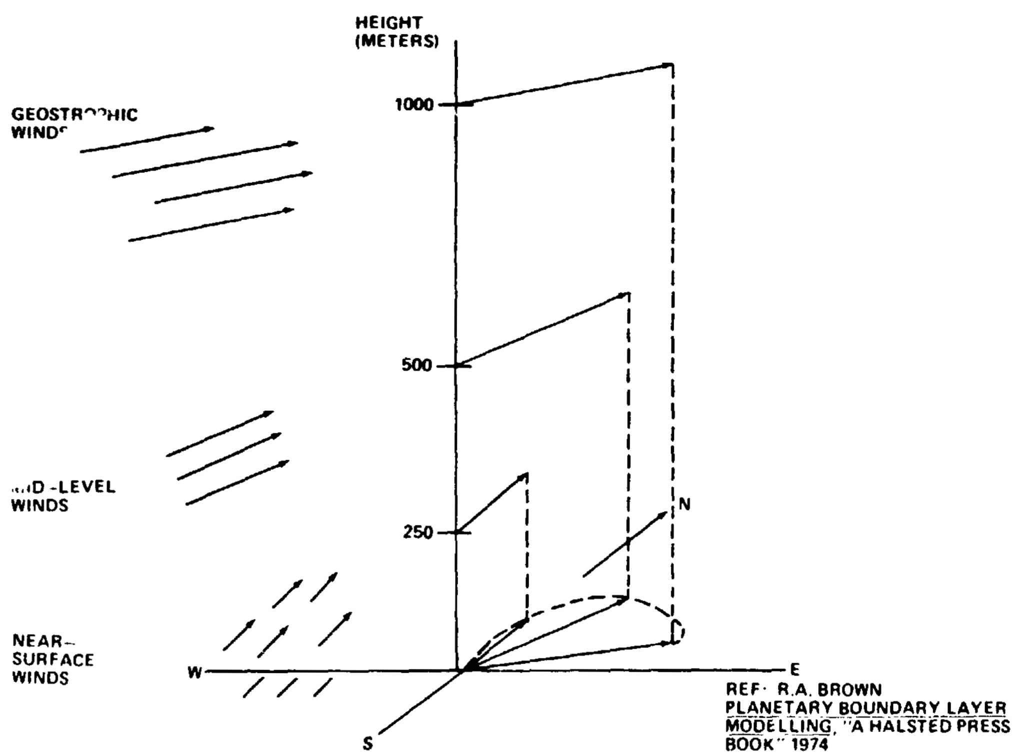


Figure 16. The Ekman spiral and hodograph on projected surface.

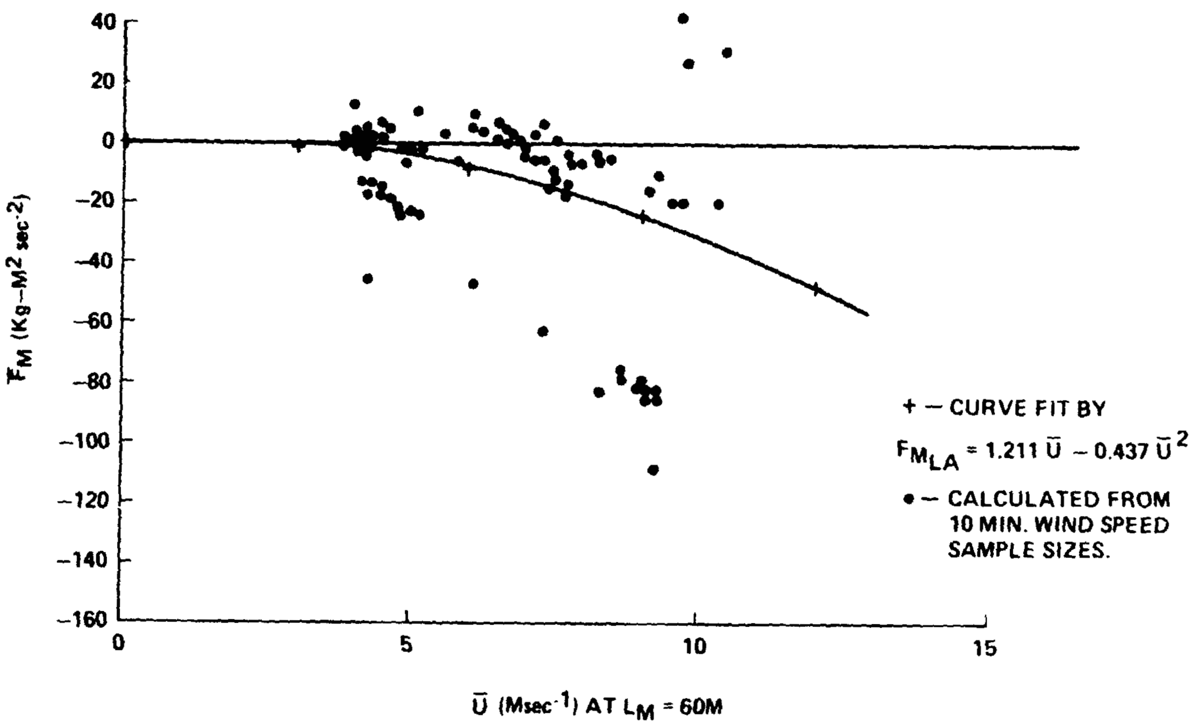


Figure 17. Mean lateral moment forces versus mean wind speed, from 150 m ground wind tower data, KSC, Florida.

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APPROVAL

PRELIMINARY STUDY OF INPHASE GUSTS AND MOMENT FORCE WIND LOADS OVER THE FIRST 150 METERS AT KSC, FLORIDA

By John W. Kaufman

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G. F. McDONOUGH
Director, Systems Dynamics Laboratory

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