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Measurements of Pressure and Force Fields on Building Models in Simulated Atmospheric Flows

Ahsan Kareem*

ABSTRACT

Measurements and analyses of space-time structure of random pressure fields and associated area-averaged loads acting on prismatic building models in simulated atmospheric flows are presented. The objective of this study is three-fold: first, a broadening of our understanding of wind induced surface pressure fluctuations around buildings; second, gaining insight into the aerodynamics of prisms immersed in turbulent boundary layer flows, e.g., sensitivity of the surface pressure field to changes in the intensity of the far-field turbulence; and third, gathering knowledge-base concerning the spectral description of integral loads on buildings and their respective correlations. This paper briefly describes the salient features of this project.

INTRODUCTION

Information of the space-time characteristics of fluctuating pressure field over buildings is necessary for design to resist damage to building cladding, window glass, mullions and other exterior architectural features. The complexity of wind-structure interaction has precluded theoretical treatment of the problem. Not only is the approach wind field complex, but the vortical flow patterns generated around a structure are complicated by the distortion of the wind field, the flow separation, the vortex formation, and wake development. The pressure fluctuations on the windward face may be related to the far-field turbulence on the basis of quasi-steady and strip theories which permit a linear relationship between the fluctuations in the pressure and velocity fields (Kareem, 1986; Kawai, 1983). These theories have been validated experimentally except for the high-frequency range where the decay of the pressure spectra is faster than that of the turbulence (Kareem, 1986 & Kawai, 1983). Based on the rapid distortion theory of turbulence, Durbin and Hunt (1980) have suggested a description of pressure spectra in the high-frequency range, which is consistent with the experimental findings.

The fluctuating pressure field on the side and leeward faces is greatly influenced by the wake dynamics, e.g., vortex shedding which places the applicability of the strip and quasi-steady theories in doubt. Hence, physical modeling of fluid-structure interaction provides the only viable means of obtaining information on the characteristics of pressure fluctuations on the side and leeward faces.

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* Professor and Director, Structural Aerodynamics and Ocean Systems Modeling Laboratory, University of Houston, Houston, TX 77204-4791

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The efforts focussing on better understanding of the nature of pressure fluctuations experimentally have been concentrated on either the exploration of the basic nature of fluid mechanics involved, or problem-focussed investigation of particular structures in boundary layer wind tunnels. The fundamental studies have been conducted by utilizing two-dimensional prismatic cylinders placed in grid generated turbulence (e.g., Cherry, et.al, 1983; Hout, J.P. et.al; Lee, 1975; Robertson, et.al, 1977; Saathoff & Melbourne, 1987; Vickery, 1966; Wedding, et.al, 1978; and Wilkinson, et.al, 1974). The investigations of pressure field over prisms of finite height exposed to simulated boundary layers have been rather limited and a sample of these studies can be found in Akins (1976), Corke & Nagib (1979), Kareem & Cermak (1984), Kareem (1986), Kareem (1988), Kawai (1983), and Surry & Djakovich (1988).

The localized point-to-point pressure fluctuations are important for the design of cladding and their attachments, but they do not provide directly useful information concerning the integral loads. In this case, the statistics of the local spatial averages of the random pressure field become more relevant. The overall loads are synthesized through space-time structure of the local averages of the pressure field which takes into account the lack of spatial and/or temporal correlation [Kareem, 1989]. The space-time averaging may be accomplished by a pneumatic averaging technique which through a pneumatic manifolding procedure determines time varying local averages of aerodynamic loads. Alternatively, a sensitive multi-component force transducer may be utilized to measure base shears or moments that can be related to the mode-generalized load spectra associated with the linear or uniform mode shape (Kareem, 1987). However, these approaches fail to provide information on the spatial distribution of aerodynamic loads acting over the surface of the building model under study. A second-generation multi-level multi-component force balance may provide distribution and correlation of dynamic wind loads (Reinhold and Kareem, 1986).

In this paper a summary of the study concerning local point-to-point pressure characteristics, locally averaged pressures and derived integral loads and load spectra obtained from a sensitive multi-component force balance is presented.

EXPERIMENTAL

Wind Tunnel

All measurements were made in the boundary layer wind tunnel of the Structural Aerodynamics Laboratory at the University of Houston. The wind tunnel has a test section 60 ft. long with a cross-section of 10 ft. x 5 ft. at the model location. Similarity requirements for simulating a turbulent boundary layer in a wind tunnel were obtained from dimensional arguments derived based on the conservation laws applicable to the lower atmosphere [Cermak, 1971]. The turbulent boundary layers under neutrally stable conditions were generated by the natural action of the surface roughness added on the tunnel floor and upstream spires. Two typical boundary layers were simulated for this study, boundary layers 1 & 2, (referred to as BLI and BLII in the text for the sake of brevity). The kinematics of the turbulent flow fields associated with BLI and BLII are similar to the flow conditions of an open country and urban environments. In BLI there is less variation of the incident mean velocity along the model elevation accompanied by a lower intensity of turbulence in comparison with BLII. The longitudinal integral length scale between the heights of 10 in. to 30 in. varied from 12 in. to 20 in.

Models

The prisms employed in this study for the measurements of surface pressure fluctuations have width to breadth ratios of 1:1.5 and 1.5:1. The aspect ratio of the height to the narrow face width is 1:5 for both prisms. The prism dimensions are 5 in. x 7.5 in. in plan and 20 in. tall. Each face of the prisms was instrumented at five levels. At each level, eight and six pressure taps were included on the wide and narrow faces, respectively. The pressure ports were connected to Setra pressure transducers. The tubing system was dynamically calibrated to determine the amplitude and phase distortion. The measured data was digitally corrected by means of a transfer function for recovering the undistorted signal. A number of combinations of taps were simultaneously monitored to map the structure of space-time pressure fluctuations in the spanwise and chordwise directions. For measurements on the alongwind faces a hot film sensor was introduced in front of the models, and for the acrosswind faces a hot film was placed in the wake. The objective of introducing these hot films was to correlate the pressure field with the far-field turbulence and wake fluctuations. The measurements were conducted for the angles of attack of 0, +5, and -5 degrees.

In addition to the surface pressure measurements, roof pressures were monitored on a square cross-section building model with adjustable height. The aspect ratio of this model could be varied between 1 and 4 with whole number increments. A quadrant of the roof was densely instrumented with pressure taps which were connected to a pressure transducer through a scanivalve. The entire measurement system was dynamically calibrated.

The prisms employed for the measurement of pneumatically averaged pressures for determining the alongwind, acrosswind and torsional loads were identical in geometry to the ones utilized in pressure measurements. For the alongwind and acrosswind loading one model was used in which locally averaged pressures were monitored at five levels. For the torsional loads the pressure taps on the model were clustered to account for the weighting function needed to introduce the lever arm (Fig. 1). Further details may be found in Kareem (1989).

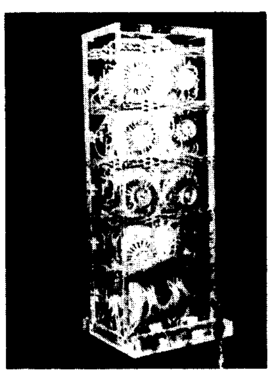

Fig. 1: A Model for Measuring Torsional Loads
Using Pneumatic Averaging

A wide range of ultra-light models were fabricated to be used in conjunction with a sensitive force balance. Models identical to the pneumatic averaging study were used to compare the results derived from the two approaches. A host of generic building shapes were modeled such that their height could be adjusted. This feature permitted investigation of the influence of aspect ratio on the aerodynamic loading. A model of a supertall building was also studied. The building represented a wedding cake configuration which permitted building study with different levels removed. Also, the loads were monitored by introducing openings in the building. In Fig. 2 these models are shown. Another group of building models representing low- to medium-rise buildings were investigated (Fig. 3).

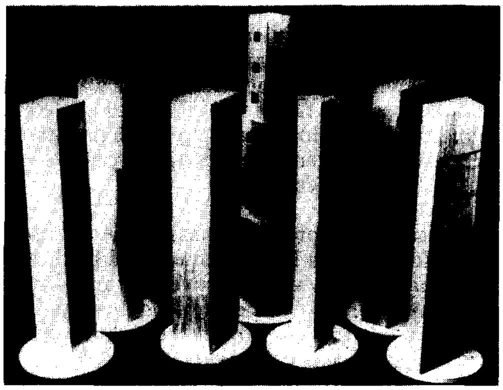

Fig. 2: Models of High-Rise Buildings for Force Balance Study

Fig. 3: Models of Mid-Rise Buildings for Force Balance Study

Data Analysis

The output from the pressure transducers was fed through a signal conditioning and an amplifier unit before online digitization. A constant-temperature hot-film and a pitot-tube were used to map the flow field characteristics. The data was analyzed to obtain the following characteristics:

a. Mean and RMS pressure coefficients
b. Signatures of simultaneously monitored time histories
c. Power spectral density functions
d. Autocorrelations
e. Crosscorrelations
f. Coherence & phase
g. Orthogonal eigenfunction expansions (Karhunen Loeve Series)
h. Statistical dependence
g. Characteristics of conditionally sampled data
h. Bicoherence & quadratic transfer functions

The output from the sensitive multi-component force balance was analyzed to determine the spectral and cross spectral density functions.

In this paper, due to limitation of length, only some of the findings are presented.

RESULTS AND DISCUSSION

Pressure Fluctuations

Spectral Description

The spectra of pressure fluctuations on the windward face is proportional to the far-field velocity spectrum except in the high-frequency range where the decay is faster. For the locations on the windward face near the faces parallel to the flow the influence of vortex shedding is present as evidenced by a narrow peak in the corresponding spectral distributions. This feature is more pronounced for the 1.5:1 prism with the flow normal to the wide face (Fig. 4). These spectral peaks become less significant in the urban flow condition. In the open country flow, the spectra of the pressure fluctuations on the lateral sides exhibit a high-amplitude spike around a reduced frequency of 0.1, which corresponds to the Strouhal frequency, is a typical characteristic of the measured spectral representations. The effects of added turbulence on the spectral peak of the pressure fluctuations on the side faces, apart from a slight reduction in the Strouhal number, are primarily a broadening and lowering of the peaks. The evolution of the spectral contents in the chordwise direction on the side face is shown in Fig. 5 of the flow normal to the broad face.

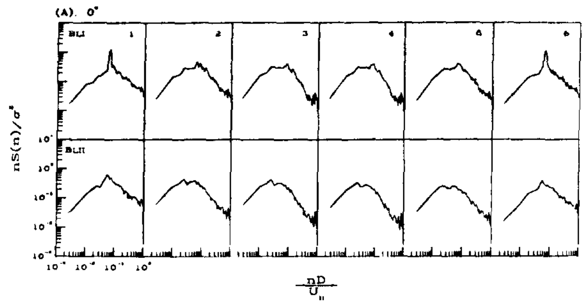

Fig. 4: Pressure Spectra on Windward Face

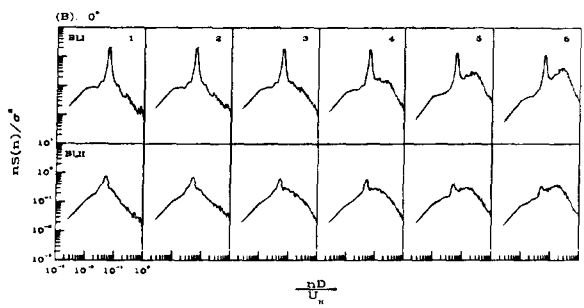

Fig. 5: Pressure Spectra on Side Face

The evolution of the spectral contents with the distance from the separation edge is highlighted by a gradual decrease at the low frequencies and an increase in the high-frequency range. This trend is present in both approach flows. The shift in frequency contents is explained by the relative location of the pressure tap with respect to recirculation and the reattachment regions. For the low turbulence intensity flows the reattachment generally does not occur unless the length of the afterbody is very long. In this case the recirculation region extends over the entire side face and the pressure field is influenced by the low frequency contents of the recirculating flow in the bubble. For higher turbulence intensity approach flow the separated flow tends to reattach. Therefore, in the separated region, which is in the recirculation zone, the low frequency contents will influence the pressure spectra, whereas, in the reattached zone their influence will be nonexistent, rather high frequency contents will dominate resulting from the reattachment of the shear layer. In summary, the spectral peak associated with the vortex shedding process is influenced by the turbulence intensity of the incident flow, whereas, the broad-band spectral contents are more influenced by the velocity field in the recirculation zone. Details of analysis concerning the mechanisms responsible in these modifications in terms of flow features of recirculating and reattachment regions will be addressed in a forthcoming report.

Multi-Point Spectral Analysis

Multi-point analysis by way of coherence and phase, and cross-correlation leads to the determination of space-time structure of the pressure and pressure-velocity fields. The coherence in the separated flow locale was high, and lower values were observed between regions in the separated and reattachment flows. For the points on the opposite faces, an abrupt phase-shift demonstrated the antisymmetric nature of pressure field induced by vortex shedding. The spanwise correlation on the side faces, like the square prism (Kareem & Cermak, 1984) are very pronounced in the separation bubble, whereas near the downstream edge relatively less evidence of correlation is exhibited. The location of the downstream edge is a region of intermittent reattachment of shear layers, experiencing pressure fluctuations which are less correlated despite the overall cyclic pattern of vortex shedding. In Figs. 6 & 7 spanwise correlations are plotted for the pressure taps located spanwise in the separation region near the separation edge and another set of taps located on a vertical generator near the downwind end of the face to demonstrate this point. The correlation is also sensitive to the approach flow at the generator near the separation edge, whereas for the downstream location the influence is negligible.

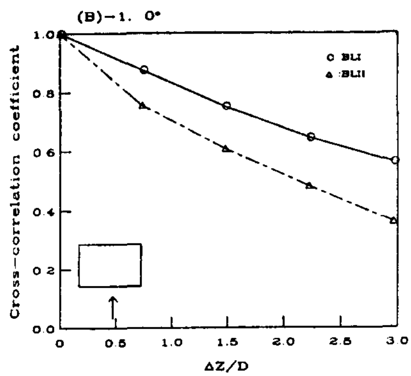

Fig. 6: Spanwise Correlation in Separation Region

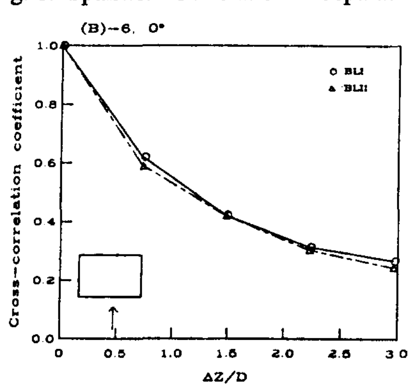

Fig. 7: Spanwise Correlation Near Downwind End

Analysis of Conditionally Sampled Data

A conditionally sampled database was established to determine the correlation of pressure peaks over the surface. The conditional sampling was initiated for different preestablished thresholds. Once a peak was monitored, the corresponding signals at other locations of interest were simultaneously monitored and the data is stored. A typical plot of conditionally sampled data pertaining to the taps located on a vertical generator of the 1.5:1 prism in the open country flow is given in Fig. 8 for the sake of illustration. The upper level tap location was used to trigger the sampling task. The data suggests distinct periodicity associated with vortex shedding at the Strouhal frequency. The periodicity is influenced by the addition of turbulence in the approach flow. The correlation length based on zero time lag varies between 0.6B to .8B (B-width of the narrow face) as the trigger level is decreased from four times the standard deviation to a single value of standard deviation. Whereas, a different version of the correlation length, which accounts for the maximum value of the correlation disregarding the time lag, varies between .7b to 1.2B. The pressure peak first appears at the upper level and sequentially evolves at the lower levels. Similarly, in the chordwise direction the pressure peak first appears near the leading edge and is convected towards the trailing edge. The data sheds light on the reattachment and the role of added turbulence on the spatial extent of the peaks. The spatial extent in the spanwise direction exceeds the chordwise direction.

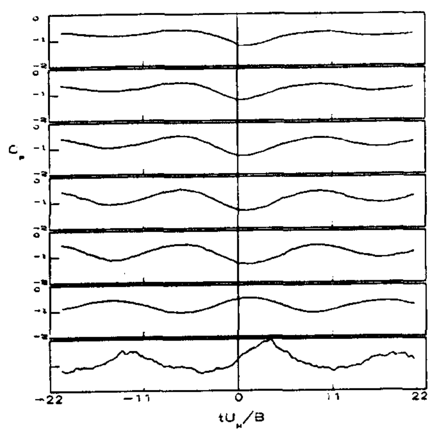

Fig. 8: Conditionally Sampled Time Histories of Pressure

Force Fluctuations

In this section results concerning wind-induced torsional loads are discussed utilizing the pneumatic averaging and the sensitive force balance approach. Utilizing the pneumatic averaging technique, torsional loads were obtained at different levels simultaneously. These were later synthesized to obtain integral loads according to a desired mode shape. The measured mode-generalized spectra were compared with those obtained from the high-frequency sensitive force balance. In Fig. 9, a comparison of the mode-generalized torsional load spectra obtained from the two techniques for the 1.5:1 model (wind approaching the broad face) is presented. The results show good agreement and suggest the validation of the spatial averaging technique briefly addressed in this paper. The small disagreement in the high frequency range is of no significance for a typical design application,which may be corrected by increasing the number of clusters of tap matrices to account for pressure fluctuations associated with short wavelengths. In these figures, for comparison purposes a uniform mode shape was used. This selection was based on the premise that the torsional loads derived from base-balance measurements are restricted to the uniform mode shape (Reinhold and Kareem, 1986). The mode-generalized spectra obtained from a force-balance study requires adjustments if the building mode shapes depart from those implied in the derivation of the force-balance theory. This is especially true for the torsional loads. These adjustments may require invoking either the quasi-steady and strip theories, or the spatial averaging technique may facilitate a precise basis for established reliable mode correction factors for any arbitrary mode shape.

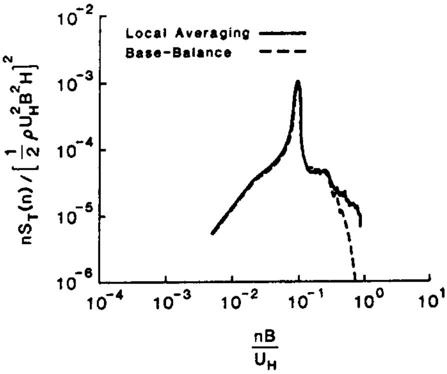

Fig. 9: Torsional Load Spectra Utilizing Pneumatic Averaging and Force Balance Techniques

CONCLUDING REMARKS

The experimental measurements and analysis represented herein have permitted the identification of the influence of turbulence on the space-time structure of random pressure field on the surface of prismatic bluff bodies exposed to turbulent boundary layer flows. The effect of increasing turbulence intensity in the incident flow is to induce early reattachment and associated pressure recovery on the side face. The spectral description of the pressure field on the side faces is comprised of broad-band and narrow-band contents associated with the recirculation in the separated flow and flow characteristics in the reattachment zone, and the vortex shedding, respectively. The spanwise correlations on the side faces are very pronounced in the separation bubble, whereas near the downstream edge less evidence of correlation is exhibited. The spatial extent of the instantaneous peaks, derived from conditional sampling, in the spanwise direction exceeds the chordwise direction. The associated correlation length is influenced by the trigger level of the signal. The integral aerodynamic loads derived from the averaging of the random pressure field over the prisms provided good agreement with the values obtained from the high-frequency force balance measurements.

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