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Correlation structure of random pressure fields

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Abstract

A random pressure field manifests different levels of load effects on structures and their components. Information on local point-to-point variation of pressure is essential for the design of cladding, or the building envelope system, whereas area averaged loads are important for the overall structural loads. Fundamental to the characterizations of pressure fields is their correlation structure which determines the resulting aerodynamic load effects. This paper focuses on the correlation structure of the pressure field on prismatic bodies of finite height immersed in turbulent boundary layer flows. Wind tunnel and numerical simulation data are utilized to study the correlation structure. Both unconditional and conditional correlations, i.e. correlation of unconditionally and conditionally sampled data, are discussed here in the light of their sensitivity to the relative location on the surface, body geometry and the approach flow characteristics.

Keywords: Random field; Turbulence; Correlation; Wind; Wind tunnel; Aerodynamics

1. Introduction

Over the past several decades much attention has been focused on the aerodynamics of streamlined bodies, however, our knowledge of the aerodynamics of sharp-edged bluff bodies in turbulent boundary layer flows is far from complete. The primary difficulty lies in the structure of the separating/reattaching flow features and their sensitivity to the approach flow characteristics. These flow-structure interactions pose difficult and interesting problems of practical interest to the aerodynamics of civil infrastructure that requires further investigation. Historically, investigations in this area have been related to the mean and fluctuating pressure fields around two-dimensional bluff bodies exposed to uniform flows (e.g., Refs. [1–5]).

Three-dimensional bodies attached to a plane surface and exposed to turbulent boundary layers experience significantly different flow conditions. Studies related to this type of flows have been rather limited and a sample of these studies, which have included correlation of the pressure field, can be found in Refs. [6–12]. Some of these

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studies also include analysis of conditionally sampled data. Computational fluid dynamics is quickly emerging as another source of determining the space–time distribution of pressure field over bluff bodies (e.g., Ref. [13]). Yu and Kareem [14] utilizing the LES model have reported correlation of pressure around bluff bodies.

This paper concerns local point pressures on prismatic bluff bodies based on experimental data in a numerically generated flow field. Analysis includes correlation structure of unconditionally and conditionally sampled data and a discussion of the possible underlying mechanisms which offer some explanation of the observed phenomena.

2. Model and flow conditions

The prisms employed in this study have width-to-breadth ratios of 1 : 1, 1 : 1.5 and 1.5 : 1. The aspect ratio of the height to the narrow face is 1 : 4 for these prisms. Most of the results discussed in this study will concern the rectangular prisms. The pressure tubing system was dynamically calibrated to determine the amplitude and phase distortion. The measured data was digitally corrected by means of a transfer function to recover the distorted signal. A total of 20 measurement configurations were employed for each flow condition. For measurement configurations on or near the front face, incident velocity fluctuations were simultaneously monitored, whereas for other configurations, wake velocity was monitored.

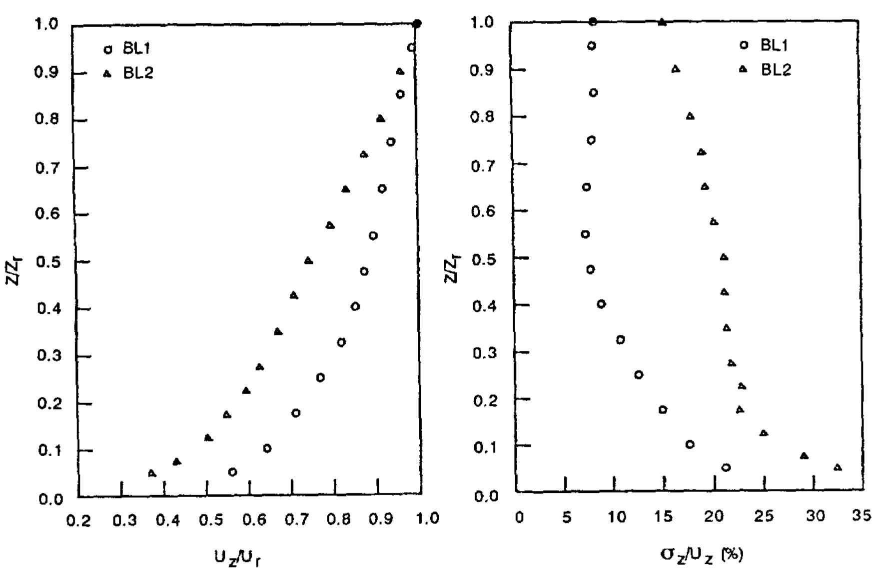

Fig. 1. Boundary layer and turbulence intensity profiles ($r = 1$ m; $\alpha = 0.16$ and 0.35).

Two approach boundary layer flows were used, namely, BLI and BLII. The wind tunnel employed has a test section 18 m long with a cross-section of 3 m × 1.5 m at the model section. 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. The kinematics of the turbulent boundary layers are similar to the flow conditions of open country and urban conditions. In BLI, there is less variation of the mean incident velocity along with a lower level of turbulence intensity in comparison with BLII (Fig. 1). The longitudinal length scale between the heights of 25.4 to 76.2 cm varied between 30.5 and 50.8 cm (model dimensions, 12.7 × 12.7 × 50.8 cm and 12.7 × 19 × 50.8 cm).

3. Numerical simulation

Two-dimensional flow over rigid rectangular prisms is simulated at Reynolds number of 100 000 using the large eddy simulation scheme. A finite-difference method based on a staggered grid is used and the convection terms are discretized by the QUICK scheme [15]. Simultaneous time histories of velocity and pressure fields are simulated. Only results concerning correlation structure will be addressed here, other details can be found in Ref. [14].

4. Discussion of results

Some of the general observations drawn from the analysis of data relevant to the correlation of the pressure field are presented first. The pressure fluctuations on square and rectangular prisms exhibit vortex shedding at the Strouhal number. While increased turbulence intensity vitiates the vortex shedding process, nonetheless pressure fluctuations still exhibit significant energy at the Strouhal frequency. This observation reconfirms author's earlier work as well as those reported by Surry and Djakovich [12]. This trend differs from Saathoff and Melbourne's [4] observation which attributes pressure fluctuations to intermittently reattaching shear layers with a little discernible evidence of vortex shedding. This may be attributed to the difference in the approach flow and flow over a two-dimensional body. Our observation was further corroborated by the orthonormal expansion of the covariance matrix of the pressure field into eigenfunctions also known as the Karhunen Loeve series [1,8,16,17]. Each eigenfunction may be assigned physical significance on the basis of its spatial description. An antisymmetric mode is generally associated with vortex shedding. In our case a major portion of energy in low-turbulence approach flow is associated with the fundamental mode, which is antisymmetric with respect to the side faces. With increased turbulence, energy shifts to higher modes with still a higher concentration in the fundamental mode. Lee [1] made a similar observation and concluded that the fundamental eigenfunction depicts the vortex shedding mode and the associated energy is reduced when the turbulence intensity of the incident flow is increased.

Furthermore, with increase in turbulence in the approach flow, an early reattachment and associated pressure recovery on the side faces is noted. The spectral description of the pressure field on the side faces has broad-banded and narrow-banded contents. These features are associated with recirculation in the separated flow, dynamics of reattaching flow, and vortex shedding. The effects of added turbulence on the spectral peaks apart from a slight reduction in the Strouhal number, are primarily broadening and lowering of the peak in the spectral density function. The evolution of the spectral contents with 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 noted in both flows. The shift in the frequency contents is explained by the relative location of the pressure tap with respect to the recirculation and 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 recirculating 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. This feature was also noted in the numerical study, where the reattachment was noted from pressure distributions for cross-sections with longer afterbodies, i.e., 1:3 and 1:4 sections. This observation was corroborated by streaklines of flow around these bodies. For the higher-turbulence approach flow, the separated flow tends to reattach even for a relatively shorter afterbody. Accordingly, in the separated flow region the spectra is dominated by low-frequency contents, and in the reattachment zone, the high-frequency contents are prevalent.

4.1. Correlation structure: Unconditionally sampled data

The most common correlation between time realizations of two processes involves unconditional sampling, i.e., no precondition is imposed regarding the amplitude of each process. This leads to correlation that represents statistically averaged quantity which determines the relationship between two processes at different time or space intervals. The area under a correlation function typically represents the scale of fluctuation. Utilizing description of such correlation of pressure on a surface, one can determine the mean square value or the spectral description of the integral loads on the surface by covariance integration scheme or through a Karhunen Loeve (orthogonal eigenfunction) expansion in time or frequency domain [7,8,18].

In Fig. 2, spanwise correlation on the side face of the two rectangular prisms is presented. Data for other faces is omitted here for brevity sake. For the case in which wind approaches the wider face (top left) the taps located on an axis close to the leading edge (B-1) exhibit highest correlation, and the correlation reduces at the trailing edge (B-6). The effect of turbulence is consistent with the earlier discussion. In the case of wind approaching the narrow face (top right), the correlation is lower in comparison with the previous configuration, though the trends remain unchanged. The associated length scales are reported inTable 1. In Table 1, configurations denote 'S' for spanwise, followed by a number representing location of the axis on which the taps are located and the last number describes building cross-section, i.e., 1: broader face upwind and 2: narrow face upwind and 3: square section. The average correlation

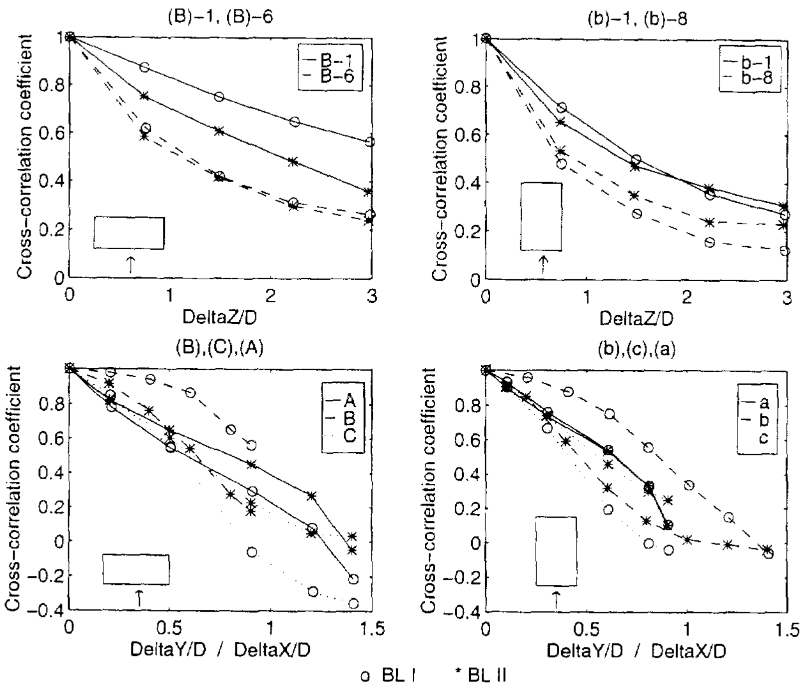

Fig. 2. Spanwise and chordwise cross correlations (B and b = streamwise; A and a = windward and C and c = leeward faces; 1 = leading edge; 6 and 8 = trailing edges).

Table 1
Correlation scales

Configuration	Boundary layer I			Boundary layer II		
	Correlation length			Correlation length		
	Average	Cond. (a)	Cond. (b)	Average	Cond. (a)	Cond. (b)
S1-01	2.94D	3.15D	4.01D	2.39D	2.53D	2.80D
S6-01	1.92D	1.83D	2.91D	1.85D	1.62D	2.37D
S1-02	2.10D	2.45D	3.14D	2.08D	2.00D	2.36D
S8-02	1.44D	1.36D	2.76D	1.71D	1.62D	2.02D
C-01	0.86D	0.88D	0.93D	0.66D	0.63D	0.74D
C-02	0.84D	0.75D	1.05D	0.47D	0.31D	0.50D
S1-03	2.12D	—	—	1.71D	—	—
S4-03	1.42D	—	—	1.21D	—	—
C-03	0.76D	—	—	0.58D	—	—

Note: (a) Correlation at zero time lag; (b) maximum correlation at any time lag; D, narrow face dimension.

length is based on unconditional data. In summary, the spanwise correlation length on the side faces is very pronounced in the separation bubble, whereas near the downstream edge, correlation deteriorates which is further worsened in BLII. This is a region of intermittent reattachment in which pressure fluctuations are poorly correlated despite the overall cyclic pattern of vortex shedding. An observation that needs further confirmation concerns the similarity of pressure correlation in the reattachment region to that of the approach flow, suggesting significant influence of the approach flow on the pressure in the reattached region.

In the chordwise direction, for the narrow and wide side faces, the correlation is plotted in Fig. 2. Results for stagnation and leeward faces are also included. The pressure shows high correlation on the side face for flow parallel to the narrow face, whereas for the prism with the wide face parallel to the flow, due to a longer afterbody, results in the correlation deteriorating faster and is further influenced by an increase in approach flow turbulence. The correlation on stagnation and leeward faces is, in general, lower than the side faces, whereas the stagnation face shows higher correlation than the leeward. The results for the square prism are not plotted here for brevity, but the correlation length data for all three shapes are provided in Table 1. The correlation length in each case is lower than the narrow face width and an increase in the afterbody length and an addition of turbulence in the flow result in further reducing the correlation.

The chordwise data from the numerical simulation for the square two-dimensional prism reconfirms the experimental observations that the correlation structure remains uniform over the separated regions of the side faces, whereas the front and rear faces are characterized by sharply increasing or decreasing correlation. This points at the dominant presence of antisymmetric correlation pattern associated with vortex shedding. This observation was also noted from the examination of the streaklines. The numerically obtained results are in a very good agreement with the experimental results (Fig. 3). The covariance matrix of the chordwise pressure was expanded to obtain eigenvalues and eigenfunctions. The first five eigenvalues contained 98% of the

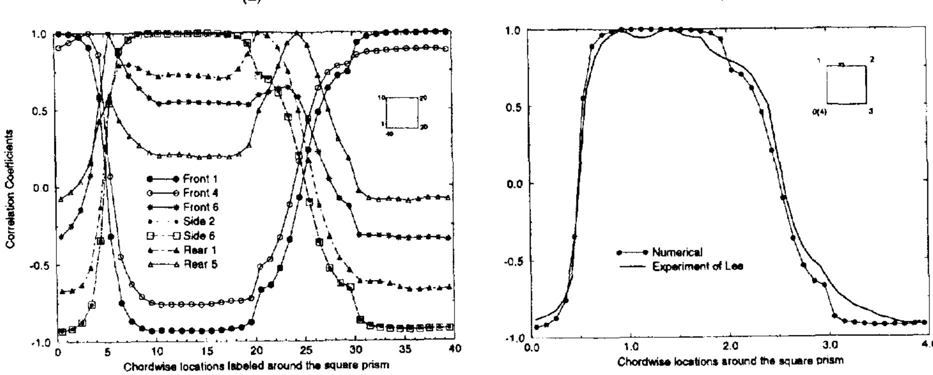

Fig. 3. Chordwise correlation of numerical simulation.

total energy. The percentage of energy in the first five modes is, respectively, 74%, 16.1%, 3.8%, 3.3% and 1.3%, which are in good agreement with wind tunnel results of Lee [1]. It is also noted that the first eigenfunction, being antisymmetric, dominates the dynamics of pressure fluctuation.

4.2. *Correlation structure: Conditionally sampled data*

Isolated high negative pressure peaks on the surfaces of bluff bodies often raise concern for the severity of the associated loads on structures. While these isolated peaks present a dramatic first impression, they are generally believed to translate into a relatively small increase in the overall loads, as it is commonly held that their spatial correlation is limited. Under separated shear layers on the side faces of tall buildings, long span bridge decks and over canopies of stadiums and roofs of train stations, the spatial extent of these peaks may be quite significant [19]. Kareem also stressed their existence in his discussion of Melbourne [19]. In order to examine the correlation structure of such extreme excursions, conditional sampling is utilized to selectively analyze the data. The data is sampled at the time of occurrence of a pre-defined level of peak in the pressure data at a prescribed location which helps to map the space–time structure of high peak pressure excursions. The correlation scales, derived from conditional data, depending on the trigger level of the reference signal, determine the effectiveness of the peaks toward contributing to the tributary loads in the separated flow regions.

The conditionally sampled data were collected for both rectangular configurations. The conditional sampling was done by using the taps at the top level for the spanwise cases and near the leading edge for the chordwise direction by setting trigger level at three times the RMS value. The conditionally sampled data is an average of 15 snapshots of conditional data. First, the results are discussed for the taps located on the side faces of the prism with flow parallel to the narrow face. In Fig. 4, a zoomed snapshot of the conditionally sampled data is shown; the top two figures represent data at the leading edge for BLI and BLII. A total of seven channels of data are presented. Channels 1–5 are on one axis close to the leading edge and channel 6 is at the top level on the opposite face and channel 7 is the wake turbulence monitored by a hot-film located in the wake. Both conditional and unconditional time histories exhibit strong evidence of vortex shedding which is vitiated in the presence of turbulence, i.e., in BLII. Pressure tap 6 shows a complete out of phase pressure signature along with the hot-film data. Both channels 6 and 7 are also dominated by periodicity associated with vortex shedding. In the case of trailing edge axis (bottom two figures for BLI and BLII), the trend is similar to that of the leading edge. It is also noted from slight time shifts in these time histories that for the spanwise pressure fluctuations the negative pressure peaks initiate at the top level and progress downwards in sequence at lower levels.

The conditional data for flow parallel to the wide face are not shown here for brevity. The trends are rather similar, e.g., the evidence of vortex shedding at the leading edge in BLI which is slightly influenced in BLII. Due to long afterbody, the pressure and wake velocity signatures are devoid of periodic components as the

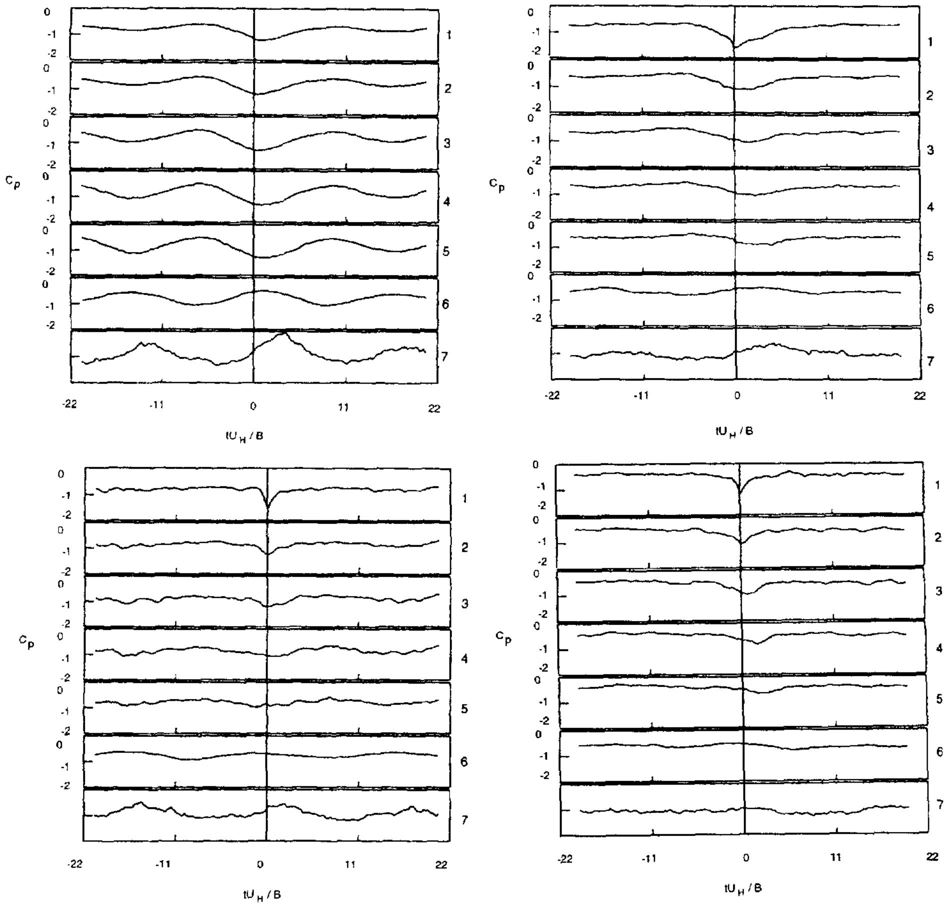

Fig. 4. Snapshots of conditional pressure data.

periodic vortices formed, due to separation, rapidly diffuse and decay. Li and Melbourne [5] reported that incident turbulence is primarily responsible for pressure fluctuations near the leading edge of rectangular cylinders with aspect ratio of 2 or larger, whereas vortex shedding dominates the square prism. The lack of vortex shedding for longer afterbody prisms in their study is despite the two-dimensional configuration which generally have higher vortex strength and associated core radius of the vortical structure [20]. This observation could not be corroborated, as the present study was limited to an aspect ratio of 0.5, 1 and 1.5. However, evidence based on other experimental studies and numerical data suggests that as the afterbody length increases the dominance of vortex shedding reduces concomitantly.

The conditionally sampled pressure signatures for the chordwise direction are not presented here; only a summary of observations is given. Beginning with the shorter side face, the data showed very dominant oscillations associated with vortex shedding which were slightly reduced in BLII. For the longer side face the chordwise data reflected the trends noted in the spanwise direction, i.e., the influence of distance from the leading edge and the presence of turbulence on the pressure signatures. Again, in the chordwise direction, a slight time shift is noted as the tap distance increases from the leading edge.

The peak pressure length scales are also reported in Table 1. These results for the spanwise direction show that the length scales for the conditionally sampled pressure fluctuations near the leading edge are higher in BLI as compared with the averaged correlation scales suggesting that the high level of pressure fluctuations are very well correlated. The trend is similar in BLII, with a few exceptions where the two are almost equal. The correlation length irrespective of the time lag gives even higher scale, which is larger than the averaged case for all the measured data (case b). All length scales reduce in BLII which confirms the observations made in the preceding sections. For the trailing edge locations, where the flow is influenced by the length of the afterbody and the turbulence, the length scales based on the averaged correlation are higher than the conditional, suggesting a lack of spatial extent of larger peak pressures which are more isolated in nature and less consistent spatially. In the chordwise direction, for the shorter afterbody, the length scale in both boundary layers is almost equal, whereas in the long afterbody case, the averaged correlation length is higher. This confirms lack of consistent structure in the pressure field on prisms with long afterbodies. This trend is further reinforced with the addition of turbulence. The results reported above may be influenced by the trigger level. As the trigger level is increased, the correlation length may experience a downward trend, with the exception of pressure along the leading edge in lower turbulence approach flows. The conditional scale was found to be slightly lower than the average due to relatively higher threshold for the triggering channels in the study reported by Surry and Djakovich [12].

5. Concluding remarks

The experimental and numerical results presented here have facilitated the identification of the influence of turbulence on the space–time structure of pressure fields on bodies of different aspect ratios. An increase in incident turbulence induces early reattachment and associated pressure recovery on the side faces. The spanwise correlation of both conditional and unconditional pressure data in the separation bubble is very pronounced, suggesting existence of spatially and temporally well-correlated peaks in pressure. This trend is reduced on the downstream edge of the side face which is further deteriorated as either the afterbody length, turbulence level, or both, increase. The spanwise correlation scales are larger than the chordwise direction, reflecting the influence of vortical flow structures.

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