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# Numerical Investigation of the Influence of Aspect Ratio on Flows Around Bluff Bodies

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ABSTRACT: A numerical simulation of flow around rectangular 2-D prisms of different cross-sectional aspect ratios, ranging from 0.3 to 7.0, is conducted at a Reynolds number of $10^5$. The large eddy simulation (LES) scheme is utilized to solve the 3-D Navier-Stokes equations using a finite volume method on a non-uniform grid, with the Smagorinsky closure model representing the subgrid scale viscosity. This study identifies the influence of aspect ratio on flow features of the velocity/pressure field, i.e., instantaneous vorticity/pressure contours, mean flow streamlines, mean/RMS pressure distribution around the prism, base pressure, mean/RMS drag/lift coefficients, spectral description of drag/lift time history, the associated wavelet based scalograms, wavelet instantaneous frequency spectra and the Strouhal number. Results exhibit salient features in the flow field and associated pressure/aerodynamic forces due to changes in the after body length, demonstrating good agreement with observations from wind tunnel experiments. Findings include identification of the critical depth/breadth ratio and fluctuations in the drag/lift forces, containing features that vary with aspect ratio. A time-frequency analysis is introduced to identify the transient nature of these fluctuations. Wavelet based signal processing schemes combined with instantaneous vorticity/pressure contours are utilized to further highlight temporal variations in the frequency contents of these fluctuations and their influence on the force coefficients.

KEYWORDS: bluff body aerodynamics, large eddy simulation, aspect ratio, turbulence.

## 1 INTRODUCTION

The understanding of how body geometry influences subsequent changes to the velocity and pressure fields is important for many aspects of engineering. For rectangular prisms, the separation and reattachment characteristics of the flow are controlled by the prism aspect ratio and the upstream flow characteristics. Previous experimental studies involving rectangular prisms have provided important results concerning the pressure distribution on the prism faces, the lift and drag coefficients and the Strouhal number. This study extends the parameter range of previous work [1], investigating the mean streamlines for the flows, relating the formation length to the base pressure and drag coefficients, as well as revealing the peak in drag force for shorter bodies.

The current work employs a three-dimensional large eddy simulation (LES) scheme to study the velocity and pressure fields around rectangular prisms. By examining time-averaged streamline contours, mean and root-mean-square (RMS) pressure distribution on the prism surfaces, and integral quantities covering drag, lift and Strouhal number, the current simulation highlights the variation of important flow field characteristics with respect to aspect ratios and the inter-dependence of these features. The numerical results are in good agreement with the available experimental data.

## 2 NUMERICAL METHOD

The incompressible, three dimensional Navier-Stokes equations, recast in LES form, are solved numerically:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{\partial \overline{P}}{\partial x_i} + \left(\nu + \nu_{SGS}\right)\frac{\partial \overline{s}_{ij}}{\partial x_j}, \tag{2}$$

where

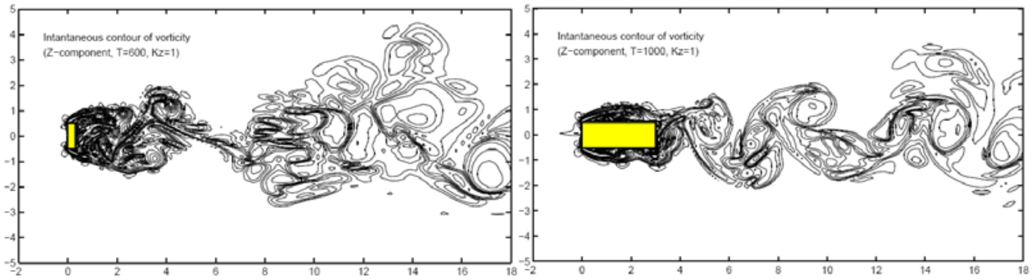
$$\nu_{SGS} = \left(C_s \Delta\right)^2 \cdot \left(\tfrac{1}{2}\overline{s}_{ij}\overline{s}_{ij}\right)^{1/2}, \quad \text{and} \quad \overline{s}_{ij} = \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}. \tag{3}$$

The governing equations are non-dimensionalized using the length of the windward surface of the rectangular cross section and the inflow velocity. The Navier-Stokes equations, together with the boundary conditions, are solved using a finite volume method. The convection terms are discretized with the QUICK scheme, and the diffusion terms are discretized using the central difference method. The Leith method is employed for temporal marching, and the pressure field is solved using successive over-relaxation.

## 3 NUMERICAL SIMULATION RESULTS

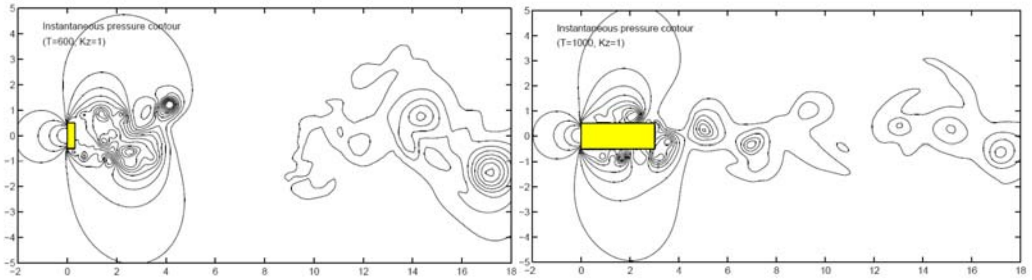
### 3.1 *Velocity and Pressure Field Results*

Fig. 1 shows an example of the instantaneous vorticity contours for prisms with aspect ratios 0.3 and 3.0. Fig. 2 shows an example of the instantaneous pressure contours for prisms with the same aspect ratios. Staggered low pressure centers exist at the core of the vortices, showing the behavior of the flow as reflected in both contour plots.



(a) (b)

Figure 1: Instantaneous vorticity contours for rectangular prisms with aspect ratios (a) 0.3 and (b) 3.0.



(a) (b)

Figure 2: Instantaneous pressure contours for rectangular prisms with aspect ratios (a) 0.3 and (b) 3.0.

The mean and RMS pressure distributions on the side face of prisms with varying aspect ratios are presented in Fig. 3, demonstrating that an increase in the streamwise body length corresponds to a concomitant pressure recovery on the side face. The mean and RMS pressure results reveal that flow fields around prisms with aspect ratios of 1.5 and 2 do not exhibit reattachment. However, it is noted that though the flow on the side of the prism of aspect ratio 2 does not reattach, the RMS pressure is not decreasing and thus demonstrates a tendency toward pressure recovery.

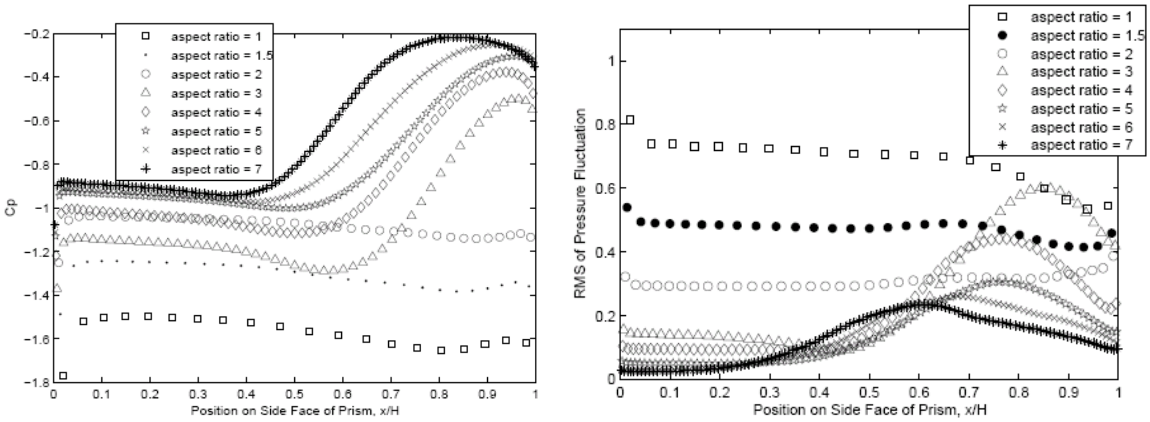
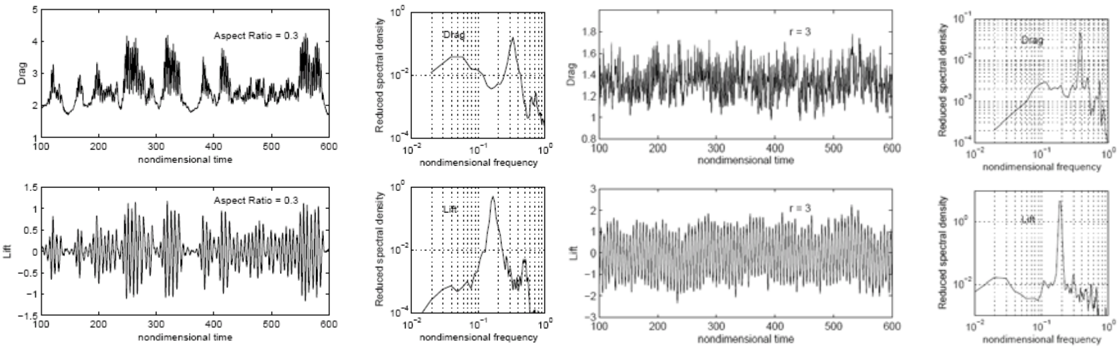


Figure 3: Comparison of mean and RMS pressure distribution on side face of rectangular prisms with different aspect ratios.

### 3.2 *Drag and Lift Forces*

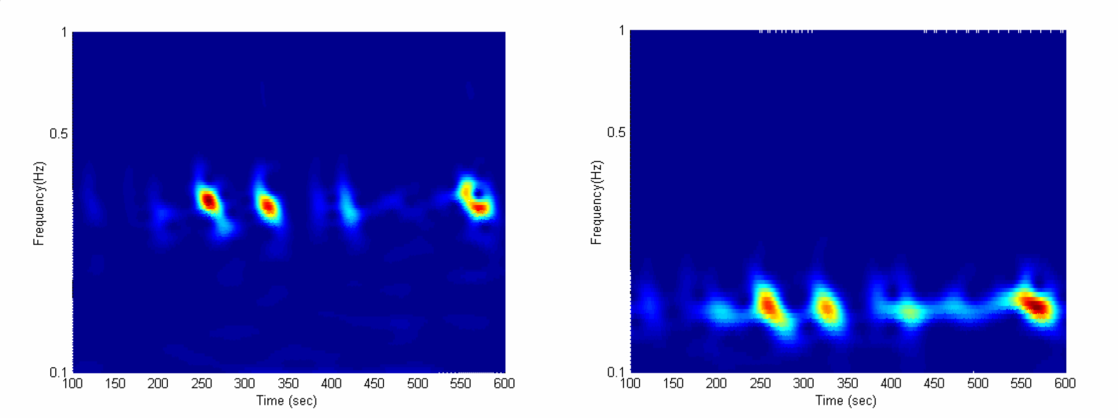
Drag and lift force history for aspect ratios 0.3 and 3.0, along with corresponding power spectra, are shown in Fig. 4. Examination of the drag and lift force history for all aspect ratios reveals distinctive features both above and below the critical value. For aspect ratios below the critical value, 0.5, intermittent behavior (periods of high or low drag force) occurs, while beyond the critical value the drag force history has less intermittent behavior. Wavelet based scalograms for the drag and lift forces for aspect ratios 0.3 and 3.0 are shown in Fig. 5, which reaffirm the intermittent bursts of energy for aspect ratio of 0.3 and relatively more sustained level of fluctuations for aspect ratio of 3.0. Examination of scalograms also suggests that the intermittent structures reside within the dominant frequency band of the lift and drag fluctuations

The mean drag and lift coefficients were examined for various aspect ratios. The maximum drag coefficient value, approximately 3, occurred near the aspect ratio of 0.5. This peak occurs at the same aspect ratio as the base pressure, and is coincident with the minimum formation length. Beyond this peak the mean decreases with increasing aspect ratio, showing good agreement with experimental results. Additionally, the RMS values of both the drag and the lift coefficients decrease with increasing body length, beyond an aspect ratio of 3, due to flow reattachment attributed to the presence of the afterbody for these aspect ratios.

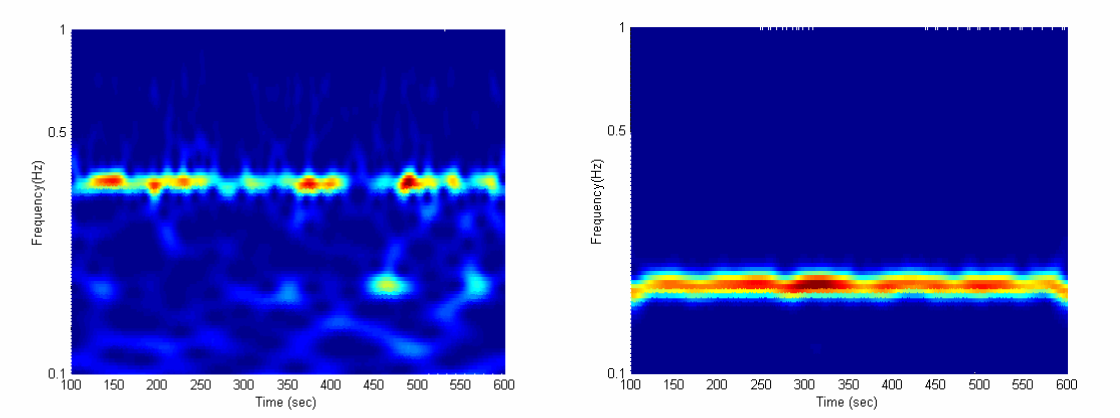


(a) (b)

Figure 4: Drag and lift force fluctuation history and power spectra for prism with aspect ratios (a) 0.3 and (b) 3.0.



(a) Drag, aspect ratio = 0.3 (b) Lift, aspect ratio = 0.3



(c) Drag, aspect ratio = 3.0 (d) Lift, aspect ratio = 3.0

Figure 5: Wavelet based scalogram of drag and lift force fluctuation time history for aspect ratios 0.3 (a, b) and 3.0 (c, d), respectively

## 4 CONCLUSIONS

This paper demonstrates the effectiveness of a numerical scheme in studying flow around bluff bodies. By comparison with experiments, it is noted that all results, encompassing a wide range of aspect ratios, show satisfactory agreement. However, a small discrepancy is noted in the aspect ratio at which the peak drag value occurs. This observation is being further examined in light of the inflow conditions used in experimental data. The separation/reattachment characteristics of the flow along the prism side faces are clearly visualized through the mean streamlines and instantaneous pressure and vorticity contours. Patterns identified in the flow by the streamlines corroborate with the mean and RMS pressure distributions along the side faces. Since computational results are in good agreement with applicable experimental data, the numerical scheme presented provides a useful framework for further investigations regarding bluff body flows of civil engineering interest, e.g., flow fields and their load effects on buildings and bridge decks.

## REFERENCES

1 D. Yu and A. Kareem. Parametric study of flow around rectangular prisms using LES. *Journal of Wind Engineering and Industrial Aerodynamics*, 77&78:653-662, 1998.