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Application of a spectrum-modified turbulence closure in bridge design

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SUMMARY:
Conventional turbulence closures do not perform well in flows dominated by vortex shedding. In bridges, vortex shedding occurs from several components one of which consists of a large rectangular section which is submerged to provide a dry space for pier construction. The interaction of the wind with this structure often leads to large-amplitude oscillations that hinder its accurate placement leading occasionally to delays in the construction schedule. The work reported here was conducted in response to a request from a bridge design team to recommend practical measures to reduce the impact of vortex shedding on this structure - specifically to reduce the mean drag and fluctuating lift forces that act upon it. Computations were thus performed to assess the performance of two methods for flow control using a turbulence closure that was modified to accurately capture the forces due to vortex shedding. The results obtained indicated that significant benefits can accrue by rounding the corners to a specified radius of curvature, and by inserting a splitter plate of a specified length on the leeward side of the structure. These recommendation were implemented in practice and were reported to perform as predicted.

Keywords: turbulence closure, vortex shedding, flow control, case study

1. INTRODUCTION

Almost all flows relevant to wind engineering are turbulent, and many are also unsteady in the mean flow due, most commonly, to the occurrence of vortex shedding. In bridges, vortex shedding occurs from the decks, suspension cables, and from caissons which are large sharp-cornered rectangular structures that are used to provide dry space for pier construction. In general, the prediction of the aerodynamic loads is achieved by one of two approaches: Large-Eddy Simulations and URANS. In this work, we utilized the URANS approach since the objective was to contribute to an actual bridge design process by performing extensive, time consuming, parametric studies to optimize the design. Conventional turbulence closures used in URANS often fail badly in capturing the effects of vortex shedding on the aerodynamic loads (Murakami et al., 1990). Specifically, the magnitudes of the mean drag force and the root mean square of the lift force fluctuations are seriously underestimated. Various reasons for this outcome have been put forward and several modifications were proposed to improve the performance of the turbulence closure. Among these is one put forward by Younis & Zhou (2006) who argued that the failure is due to the consequences of the departure of flows with vortex shedding from the assumption of spectral equilibrium which provides for modeling the rate of turbulence energy dissipation which occurs at the small-scales of turbulence motions in terms of quantities associated with the large-scale motions. This model has been shown to accurately predict the observed reduction strength of vortex shedding by rounding the corners of rectangular structures and, separately, by the deployment of a splitter plate in the separated wake (Dai et al., 2018). These results set the objectives of this work: to adopt a well-validated turbulence closure with demonstrable capabilities in two different flow-control applications and use it to recommend design changes based on the simultaneous deployment of both methods to mitigate the effects of vortex shedding from a full-scale structure.

2. THE MODIFIED TURBULENCE MODEL

Details of the standard $k-\varepsilon$ model will be familiar to researchers with interest in CFD and hence will not be presented here. Regarding the spectrum-sensitized modification, it concerns the source terms in the ε equation which are given by:

$$S_{\varepsilon} = \frac{\varepsilon}{k}(C_{\varepsilon 1}\, P_k - C_{\varepsilon 2}\, \varepsilon) \tag{1}$$

where P_k is the rate at which energy is transferred from the mean flow to the turbulent fluctuations.

The formulation of Eq. (1) encapsulate the assumption of spectral equilibrium: energy that is generated at the large scales of turbulent motions cascades across the energy spectrum passing via increasingly smaller-scale motion until it is dissipated by viscous action. The term ε/k specifies the rate at which the transfer of energy occurs. While this formulation has proved satisfactory in a number of steady flows, it becomes questionable in flows where vortex shedding is present. In these flows, measurements of the turbulence spectrum show the occurrence of direct input of energy into the turbulence spectrum at the Strouhal frequency (Durao et al., 1988). This suggests the need to include in the model a contribution to the positive source of ε to supplement that made by P_k. Younis $ Zhou (2006) obtained an expression the additional generation term that involved multiplying the coefficient $C_{\varepsilon 1}$ by a term T that has the form:

$$T = \left(1 + C_t \frac{k}{\varepsilon} \frac{1}{Q+k} \left| \frac{\partial (Q+k)}{\partial t} \right| \right) \tag{2}$$

where Q is the mean-flow kinetic energy $\left(=0.5(U^2+V^2+W^2)\right)$. The model coefficients are assigned the values given in Table 1:

Table 1. Turbulence model coefficients.

C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	C_t	σ_k	σ_ε
0.09	1.45	1.90	0.38	1.0	1.3

3. RESULTS AND DISCUSSION

The originally-designed structure was in the form of a sharp-angled rectangle having cross-sectional dimensions of $B = 29.4$ m and $D = 18.8$ m (where B is the dimension in the direction of flow, and D is normal to it) giving an aspect ratio of $B/D = 1.564$ (Fig.1). The computations

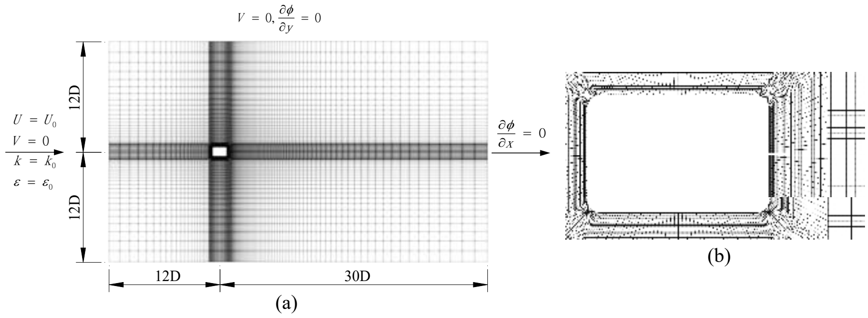

Figure 1. Computational grid and boundary conditions

were performed with the OpenFOAM software. Discretization was second-order accurate in both space and time. Grid independent results were obtained with a grid consisting on 19,394 nodes and a time-step size limited by a Courant number of 0.6.

To illustrate the need for the turbulence model modification, computations were performed for the structure as originally-designed using both the standard and modified models. The predicted time series of the lift and drag coefficients are presented in Fig. 2. As expected, the standard model obtains almost negligible fluctuations in the lift coefficient while the mean drag coefficient is significantly lower than that obtained with the modified model (see Table 2). These characteristics are similar to those obtained for the flow around a square cylinder for which experimental data were available to confirm the accuracy of the modified model.

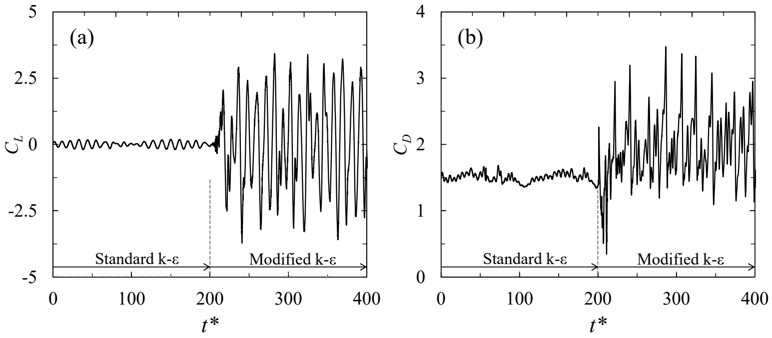

Figure 2. Time histories of (a) the lift coefficient and (b) the drag coefficient as predicted by the standard and modified models. The results are for sharp full-scale geometry.

Table 2. Predicted lift and drag coefficients for the full-scale structure

	$\overline{C_D}$	C'_L	C'_D	St
Original design	2.006	1.781	0.455	0.091
Rounding corners + Splitter plate	0.523	0.579	0.118	0.097
% Change	−73%	−34%	−74%	+6.6%

The two passive flow-control methods were considered for implementation, by rounding the sharp corners to a radius r and by the installation of a splitter plate of length L in the leeward side. Experiments have shown that the effectiveness of these methods depend respectively on the ratio r/D and L/B. Practical considerations impose some constraints that necessitate departures from the ideal ratios. Thus valuable work space would be lost by assigning a large value to r while a too long a splitter plate would interfere hinder movement around the structure. Compromises had therefore to be found and in this work, by performing extensive parametric studies, it was found that a satisfactory outcome can be achieved by assigning these parameters the values of $r/D = 0.111$ and $L/D = 0.1$. Translated to the full-scale dimensions, these ratios yielded a radius of curvature $r = 2.1$ m and a splitter-plate length $L = 2.94$ m.

The consequences of the implementation of these design modifications are shown in Fig. 3. Plotted there are the time histories of lift and drag coefficients showing these quantities as obtained for the original design and subsequently after the rounding the corners and the installation of the splitter plate. It is evident that by implementing the two flow-control methods in the full-scale design, substantial reductions in the magnitudes of the mean and fluctuating lift and drag forces can be achieved. Of particular importance is significant reduction in the fluctuations of the lift coefficient since these are responsible for the undesirable large side-to-side movement observed in the construction process. In quantitative terms, the changes wrought by the design modifications are presented in Table 2. Based on these results, it was decided to incorporate these modifications into the actual final design.

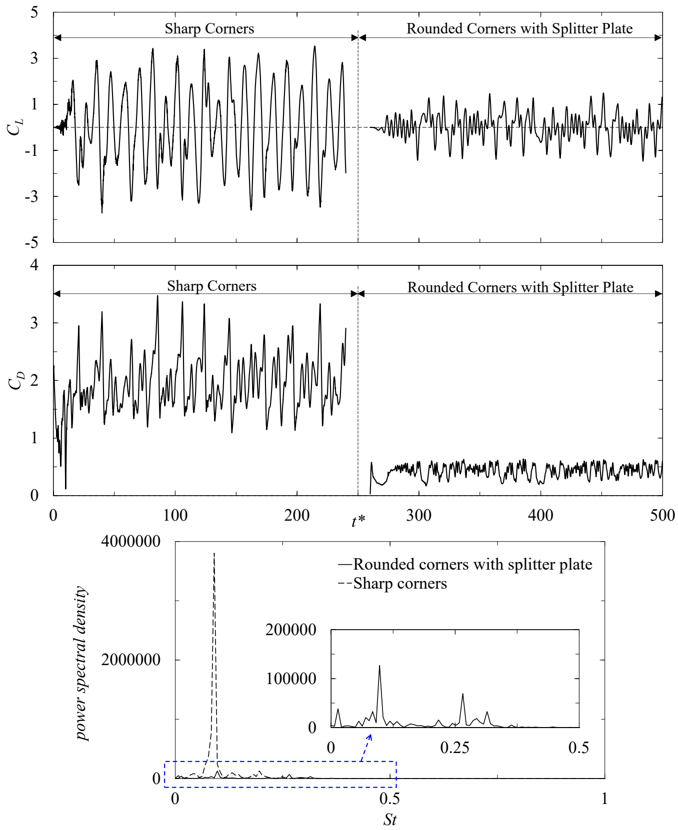

Figure 3. Time histories of the lift coefficient (top) and the drag coefficient (bottom) for the full-scale structure showing the difference between the original design and the present recommendations

4. CONCLUSIONS

Wind flow around sharp-cornered rectangular structures invariably leads to the occurrence of vortex shedding with generally undesirable consequences requiring the implementation of measures to reduce their impact. The use of CFD to explore the performance of such measures is hampered by the inability of conventional turbulence closures to fully account for the effects of vortex shedding. In this paper, we used a modified closures to predict and optimize the performance of two alternative measures for vortex-shedding control. The results of this study were incorporated in the final design and have proved effective in the field.

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