August 27-31, 2023
FLORENCE - ITALY
ICWE 16
16th International Conference on Wind Engineering

Computation of vortex shedding with a spectrum-modified turbulence closure

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SUMMARY
Most CFD applications in engineering design continue to involve the use of a two-equation turbulence closure, typically the k-ϵ model or one of its many variants to close the time-averaged Navier-Stokes equations. It is well established that this model fails badly in capturing the occurrence of vortex shedding from bluff bodies. Some variants of it do indeed capture the occurrence of vortex shedding but fail in predicting the correct magnitude of the unsteady lift and drag forces whose accurate prediction is an essential prerequisite to the calculation of the aeroelastic response of flexible structures. In this paper, we assess the performance of a model that has been adapted to properly account for the interactions between the organized mean-flow periodicity and the random turbulent motions. The test cases include the well-documented flow around a square cylinder at high Reynolds number as well as a cylinder with rounded corners intended to reduce the strength of the shed vorticies and hence of their induced fluctuations.

Keywords: Vortex shedding, turbulence spectrum, flow control

1. INTRODUCTION

The prediction of time-dependent flows around structures such as towers is fraught with uncertainties. These arise from numerical considerations that are related to issues such as stability, convergence, and accuracy and from modelling considerations such as the choice of a model to represent the effects of turbulence in appropriately-averaged Navier-Stokes equations. While Large-Eddy Simulations (LES) seemed to offer the prospect of an accurate, robust and practical tool for engineering design, and one which is free of the empiricism necessary in more conventional turbulence closures, the use of LES in practice has been quite limited, despite the wide-spread availability of enormous computer resources. The reasons for this are manyfold but are not of interest here. Rather, our focus is on the type of model which remains the more widely-used in practice, namely one which is based on Boussinesq's linear stress-strain relationship and which evaluates the eddy viscosity in that relationship from the solution of equations for two turbulence parameters. Of the numerous models that fall into this category, the k-ϵ model remains the one of first recourse, the one against whose performance other models are assessed. A well-documented limitation of this model is its inability to capture the occurrence or strength of vortex shedding from bluff bodies of the type frequently encountered in wind engineering. In this paper, we present predictions obtained with an adaptation of this popular model – one which takes into account the consequences of the direct input of energy into the turbulence spectrum that is observed experimentally to occur at the Strouhal frequency. The model's performance is assessed against experimental data for the benchmark flow around square and rectangular cylinders, as well as a square cylinder with rounded corners intended to reduce the magnitude of the resulting unsteady forces.

2. COMPUTATIONAL DETAILS

The simulations were performed using OpenFOAM to solve the mass and momentum conservation equations in their three-dimensional, time-dependent forms. Spatial and temporal discretization was with second-order accurate bounded schemes. A multi-block grid arrangement was used to better resolve the regions around the cylinders. Errors arising from grid resolutions were assessed using the Grid Convergence Index (GCI) method. The time-step size was restricted according to the CFL criterion with the value of the Courant number restricted to below 1.0. The PISO algorithm was used, and the convergence criterion was set to be when the normalized residuals fell below 10^{-6}. Concerning the boundary conditions, at inlet, uniform profiles of all the dependent variables were specified, based on the experimentally-quoted values of Reynolds number and relative turbulence intensity. At outlet, the flows were assumed to be fully developed while the other boundaries were assumed to be planes of symmetry.

The turbulence model involved solving the standard forms of the k and ϵ equations, with the various coefficients assigned their standard values except for $C_{\varepsilon 1}$, the coefficient that enters into the formulation of the production term of ϵ. This term, which is formed by combination of the rate of production of turbulence kinetic energy and a time scale of turbulence, has been formulated by reference to steady flows in which turbulence production is solely by the turbulent stresses and the rates of strain. In flows dominated by vortex shedding, an additional mechanism for energy generation is present, namely direct input of energy into the turbulence spectrum at the Strouhal frequency. This additional energy is then transferred through increasingly smaller scales to be finally dissipated by viscous action. To account for this additional rate of production of ϵ, the coefficient $C_{\varepsilon 1}$ is modified by multiplying it by a term T that has the form:

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

In Eq. (1), Q is the mean-flow kinetic energy ($Q = 0.5\,(U^2 + V^2 + W^2)$), and C_t=0.38.

3. RESULTS

We first consider the flow around a square cylinder at Re=20,000. The computed variation of the lift and drag coefficients are shown in Fig. 1. Presented there are results with the k-ϵ model both in its standard form and as modified by Eq. (1). As expected, the standard model yields a virtually steady flow as evidenced by root-mean-square levels of the force coefficients that are one order of magnitude smaller than reported in several experimental studies. Also shown in Fig. 1 are results obtained with the RNG variant of the k-ϵ model, and with the k-ω SST model. These show a pronounced 'beating' behavior suggesting irregular changes in the patterns of flow separation.

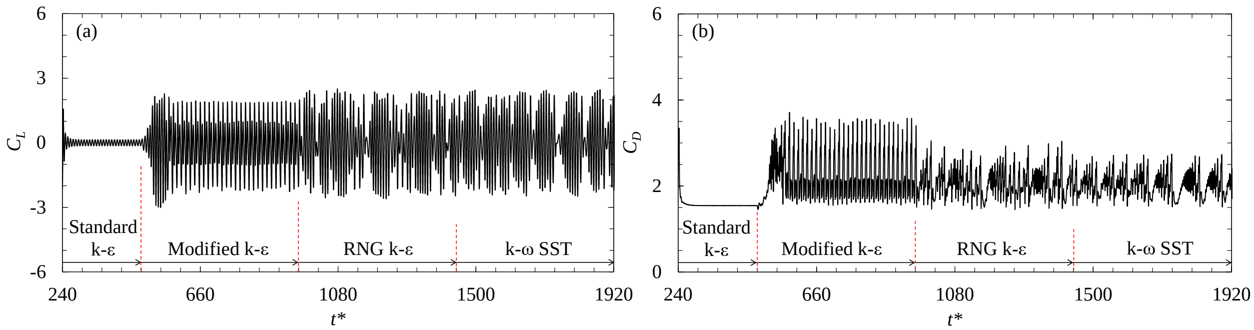

Figure 1. Computed lift and drag coefficients for square cylinder at Re=20,000.

A quantitative assessment of the modified model is presented in Fig. 2 which shows the predicted wall static pressure distribution, and the axial variation of the mean streamwise velocity. Both quantities were obtained by time averaging the variables over repeated vortex-shedding cycles. Data from various experiments are also shown and these indicate that the modified model succeeds in capturing the essential features of this flow, especially the size of the separated wake.

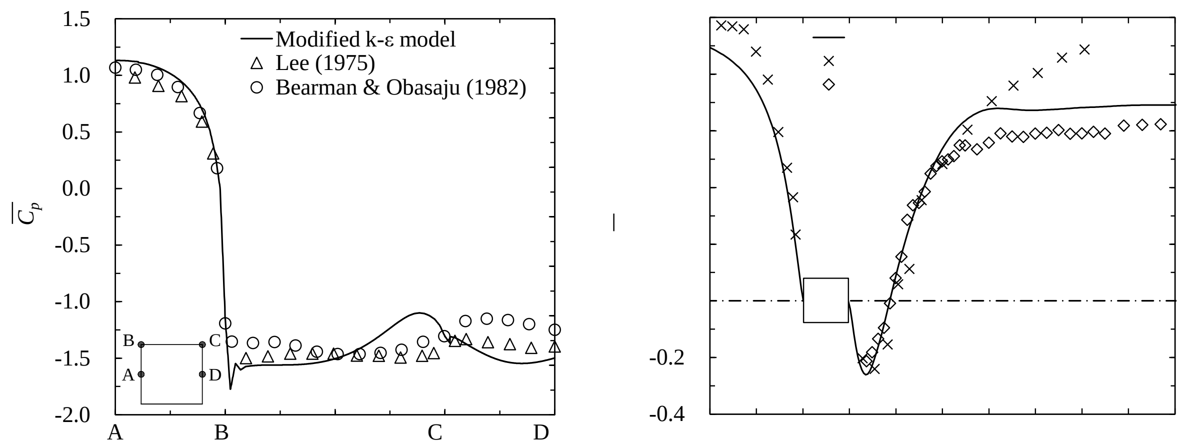

Figure 2. Modified model results for wall static pressure and axial centerline velocity.

We next consider the case of rectangular-sectioned cylinders in which the dimensions B and D represent respectively the width of the cylinder and its length in the direction of the flow. Figure 3 shows the predicted mean drag coefficient and the fluctuating lift coefficient as a function of the ratio B/D. The modified model results are represented by the filled circles, the remaining symbols represent experimental results from various sources. The predictions are in reasonably good accord with both parameters except for the B/D=3 where both parameters appear to show some departure from their otherwise monotonic decrease with increasing B/D. This behaviour, which is also apparent in an LES study of this flow, is attributed to a change in the pattern of separation and re-attachment along the cylinder's length.

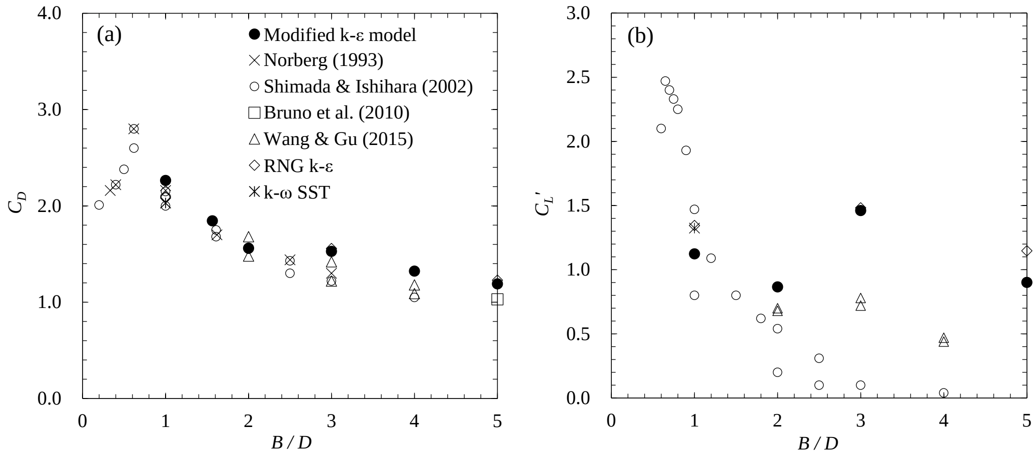

Figure 3. Predicted and measured mean drag and fluctuating lift coefficients with B/D.

Of significant practical interest is the ability to affect a significant reduction in the magnitude of the fluctuating forces through subtle modification to the geometry which, in the present case, entail the rounding of all four corners of the square cylinder. The ratio r/D, of the radius of the rounded corner to the side of the square cylinder, is the relevant non-dimensional geometric parameter and the variation of the mean drag coefficient and the root-mean-square lift coefficients with this parameter is shown in Fig. 4. Here too the comparison with the various experimental result is quite satisfactory for the drag coefficient but is significantly less so for the lift coefficient which suggest that the modified model, while succeeding in some respects, does not entirely capture the physical processes that govern the behaviour of these complex flows.

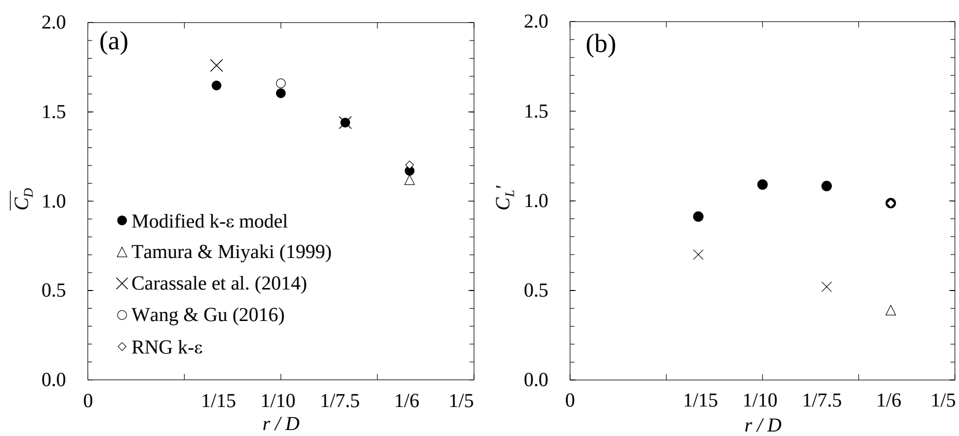

Figure 4. Predicted and measured variation of the drag and lift coefficients with r/D.

4. CONCLUSIONS

The results presented here show that the performance of the widely-used k-ϵ model in flows that are dominated by vortex shedding can be significantly improved via modification of the turbulent spectrum to incorporate the effects of direct energy input on the dissipation rate.

ACKNOWLEDGEMENTS

The financial support provided by the National Science Foundation of PR China (51208056), the Natural Science Basic Research Program of Shaanxi Province (2023-JC-YB-292) and the Fundamental Research Funds for the Central Universities, CHD (300102212909) is gratefully acknowledged.