NUMERICAL INVESTIGATIONS OF AERODYNAMIC FORCES ON 2-D SQUARE LATTICE TOWER SECTION USING TWO-EQUATION TURBULENCE MODELS

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ABSTRACT

Wind flow around lattice towers is a complex phenomenon involving interference effect between various leg/bracing members. Wind induced forces on such lattice towers are evaluated by considering overall effect on the grouped members and are related to solidity ratio. Most of the codal provisions on drag coefficient values for lattice towers are based on sectional model studies, carried out in wind tunnel for various solidity ratio values. In the present study, numerical studies on 2-D square lattice tower section have been carried out for different solidity ratio values using various turbulence models, viz. Realizable \( k-\varepsilon \) model, two versions of RNG \( k-\varepsilon \) model and SST \( k-\omega \) model. The numerically evaluated mean drag coefficient values have been compared with those provided in various international codes to assess the relative performance of these turbulence models.

Keywords: Lattice tower, Solidity ratio, Drag force coefficient, Turbulence model

Introduction

Lattice towers are being utilized for wide variety of purposes such as communication, power transmission, weather monitoring, etc. Wind flow around such type of structures is a complex phenomenon as these structures are comprised of many L-angle/circular sections as leg/bracing members. Due to the result of interferences, aerodynamic loads on neighboring members are increased considerably. Hence, it is necessary to study the fundamental flow phenomena of interference and the associated flow patterns for an appropriate description of the wind load effects on them.

In the present study, 2-D square lattice tower section comprising of L-angle sections has been considered for aerodynamic characterization. While there is considerable research on cubical and cylindrical structures, only a few earlier research studies are concentrated on irregular shapes. Modi and Slater (1983) conducted studies on wake-body interactions for a two dimensional structural angle member under stationary and vortex induced oscillatory conditions using a conventional wind tunnel with low turbulence level. Further, very limited experimental and numerical studies on structural modules comprised of a group of elements are reported in literature. Agarwal et al. (2006) investigated the low-Reynolds number flow around two square cylinders placed side-by-side using the Lattice Boltzmann Method (LBM). The effects of the gap ratio ‘s/d’ (s is the separation between the cylinders and d is the characteristic dimension) on the flow were studied. Huang et al. (2006) simulated two-dimensional, laminar and unsteady flow around cylinder arrays of unequal sizes using FLUENT at Reynolds numbers below 150 (based on the free-stream velocity and first row cylinder diameter), the flow pattern through two rows of inline cylinders and staggered
cylinders were examined. Hossain et al. (2007) presented the experimental investigation of surface mean pressure distributions on a group of cylinders with square and rectangular cross-sections under uniform flow condition for various longitudinal spacing. Islam et al. (2009) studied the two-dimensional numerical simulation of cross flow around four cylinders in an in-line rectangular configuration by using the Lattice Boltzmann Method (LBM) to find the effect of the spacing between the cylinders on the flow characteristics.

Experimental studies on lattice tower models are observed to be very limited. Carril et al. (2003) studied the wind forces on rectangular latticed tower sectional models using force balance in a wind tunnel under uniform smooth and uniform turbulent flow conditions. The evaluated force coefficients and shielding factors/interference factors were compared with various codal values. Zou et al. (2008) investigated 3-D dynamic wind loads on three kinds of lattice tower models using base balance technique in a boundary layer wind tunnel. However, numerical studies on lattice towers for the evaluation of aerodynamic force coefficients are observed to be very scanty in literature.

In the present study, mean drag force coefficients for a 2-D square lattice tower section comprising four legs of L-angle sections with different solidity ratios (varied from 0.2 to 0.67) are numerically obtained under uniform smooth flow using different turbulence models [FLUENT 6.3 (2006)], viz. Realizable $k-\varepsilon$ model hereafter referred to as RKE, RNG $k-\varepsilon$ model [Yakhot and Orszag (1986)] hereafter referred to as RNG-86 model, RNG $k-\varepsilon$ model [Yakhot et al. (1992)] hereafter referred to as RNG-92 model and SST $k-\omega$ model hereafter referred to as SST. The performance of these turbulent models in predicting the mean drag coefficient of the 2-D square lattice tower section for different solidity ratios has been assessed by comparing the predicted values with the values provided in IS: 875 (Part 3 - 1987), which are observed to be upper bound among various codal values and the values provided by AS/NS 1170.2 (2002), which are observed to be lower bound. The deviations in the mean drag coefficient predictions by the turbulence models for the above range of solidity ratios are discussed through instantaneous vorticity contour distributions and are further discussed through Fourier spectral analysis of lift coefficients also.

**Eddy Viscosity Based Two-Equation Turbulence Models**

Reynolds Averaged Navier Stokes (RANS) based two equation turbulence models are the most commonly used in practice. Among these, the $k-\varepsilon$ and $k-\omega$ based models have become industry standard and used for most of the engineering problems. The basis for the two-equation models is the Boussinesq eddy viscosity assumption, which postulates that the Reynolds stress tensor is proportional to the mean strain rate tensor through kinematic eddy viscosity ($\nu_t$) in analogy to the viscous stresses in laminar flows. Unlike kinematic or molecular viscosity ($\nu$) which is a fluid property, the kinematic eddy viscosity ($\nu_t$) depends on the flow. Dimensionally, the kinematic eddy viscosity is expressed as

$$\nu_t \propto \frac{l_o^2}{\tau_o}$$

where $l_o$ = the turbulent length scale and $\tau_o$ = the turbulent time scale.

In $k-\varepsilon$ based models, $l_o$ and $\tau_o$ are obtained using the turbulent kinetic energy ($k$) and the turbulent energy dissipation rate ($\varepsilon$). In $k-\omega$ based models, $l_o$ and $\tau_o$ are obtained using the turbulent kinetic energy ($k$) and the specific dissipation rate ($\omega$). In the present work, the following two-equation turbulence models have been considered for the analysis: RKE model, RNG-86 model, RNG-92 model and SST model, which are available in FLUENT 6.3 software.
Numerical Evaluation of Force Coefficients

In the present study, numerical simulations have been carried out on a 2-D square lattice tower section consisting of four L-angle sections, as leg members. The width of the L-angle section \( (b) \) is 0.0762 m and thickness \( (t) \) is 0.0127 m. The solidity ratio \( (\phi) \) is defined as the ratio of the effective frontal area (frontal projected area of all the individual members) of a tower normal to the wind direction divided by the frontal area enclosed by the boundary of the tower normal to the wind direction. In the present study, it has been varied between 0.2 and 0.67, i.e. clear spacing between the leg members is varied from \( 8b \) to \( 1b \). Most of the codal provisions for the force coefficients of lattice towers are based on wind tunnel studies on sectional models under uniform smooth flow conditions. Hence, at the inlet boundary condition, which is at a distance of \( 6b \) to \( 13b \) (depending on the solidity ratio) from the windward face of the tower section (Figure 1), the mean velocity is given as 9.585 m/s (corresponding Reynolds number of 50,000) with the turbulence intensity of 0.2%. The outlet boundary is chosen at a distance of \( 16b \) to \( 23b \) (depending on the solidity ratio) from the leeward face of the tower section (Fig. 1). The symmetry (free-slip) boundaries are chosen at a distance of \( 8b \) to \( 15b \) (depending on the solidity ratio) from the side faces of the tower section. Wall (no-slip) boundaries are chosen for all the sides of the angle section. Standard wall functions have been used near wall regions. The computational domain has been meshed by choosing the width of the first cell near the walls of the angle section as 0.02\( b \) based on \( y^+ \) criteria for the chosen Reynolds number. The distance of the other grid lines from the wall boundaries of all the L-angles sections to the other boundaries is varied with geometric series using a stretching ratio of 1.1 (Figure 1). The grid has quadrilateral cells counts varied in the range of 40295 to 90692 depending on the solidity ratio. Unsteady flow simulations are carried out with a time step \( (\Delta t) \) of 0.001 s. In the present study, second order implicit scheme was used for unsteady formulation and second order upwind differencing scheme was used for momentum, \( k \), \( \varepsilon \) and \( \omega \) transport equations [FLUENT 6.3 (2006)]. Further, SIMPLE algorithm [Versteeg and Malalasekera (1995)] was used for coupling pressure and velocity terms.
Results and Discussion

From the unsteady simulations, mean drag coefficient values \((C_d)\) have been evaluated using RKE, RNG-86, RNG-92 and SST turbulence models for different values of solidity ratio, viz. 0.2, 0.3, 0.4, 0.5 and 0.67. Figure 2 shows the comparison of the numerically evaluated mean drag coefficient values with the codal values [upper bound curve IS:875 (Part 3 - 1987); lower bound curve AS/NZS 1170.2 (2002)].

![Fig. 2 Comparison of mean drag coefficient values](image)

In general, the 2D four L angle sections with high solidity ratio condition corresponding to the minimum spacing experienced minimum drag than that of the all other conditions of spacing, this is especially the happening trend in interference. However, the expected value of zero for mean lift coefficient \((C_l)\) is observed for all \(\phi\) values (0.2 to 0.676). The mean drag coefficient values obtained using RNG-86 model are observed to be well comparable to the band of codal values for all the values of solidity ratio with percentage of difference of within 10% with respect to upper (or) lower bound codal values. Even though, the mean drag coefficient values obtained using RKE, RNG-92 and SST models are observed to be well comparable to the band of codal values for most of the solidity ratio values, for solidity ratio of 0.4, the mean drag coefficient values obtained using RKE, RNG-92 and SST models are observed to be significantly more by about 30%-35% than the upper bound codal value. Further, the mean drag coefficient of RKE, RNG-92 and SST models are observed to over predict the band of codal values by about 12 to 20% for solidity ratio of 0.3 also. The deviations in the mean drag coefficient predictions by the turbulence models for the above range of solidity ratios could be due to inadequacies in the evaluation of wake flow behind the windward leg members.

The comparison of local mean drag coefficient values of windward and leeward leg members obtained using RKE, RNG-86, RNG-92 and SST models and also the contour plots of vorticity distribution for various turbulence models are discussed to assess the specific deviations and the corresponding limitations in numerical simulations. The deviations in the predictions are further discussed through vortex shedding frequency of Fourier spectral analysis.
The comparison of local mean drag coefficient values of windward and leeward leg members obtained using RKE, RNG-86 RNG-92 and SST models are summarized in Table 1. It is observed from comparison that the mean drag coefficient value on single angle section (Modi and Slater, 1983) is higher in general than that on the same section while it became the part of a group. In general, results of Table 1 and typical instantaneous pressure contour (Fig. 3) also shows that the numerically obtained mean drag coefficient values of windward leg members are close to each other and similarly for leeward leg members also the computed values are observed to be same for both members, as expected.

Table 1: Numerical force coefficients for windward and leeward leg members

<table>
<thead>
<tr>
<th>Solidity ratio $\phi$</th>
<th>Numerical values $C_d$</th>
<th>RKE turbulence model</th>
<th>RNG-86 turbulence model</th>
<th>RNG-92 turbulence model</th>
<th>SST turbulence model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Windward leg member</td>
<td>Leeward leg member</td>
<td>Windward leg member</td>
<td>Leeward leg member</td>
<td>Windward leg member</td>
</tr>
<tr>
<td>0.2</td>
<td>1.08</td>
<td>0.24</td>
<td>0.78</td>
<td>0.53</td>
<td>1.22</td>
</tr>
<tr>
<td>0.3</td>
<td>1.09</td>
<td>0.32</td>
<td>0.80</td>
<td>0.42</td>
<td>1.03</td>
</tr>
<tr>
<td>0.4</td>
<td>1.24</td>
<td>0.32</td>
<td>0.81</td>
<td>0.24</td>
<td>1.24</td>
</tr>
<tr>
<td>0.5</td>
<td>0.92</td>
<td>-0.07</td>
<td>0.83</td>
<td>0.18</td>
<td>0.92</td>
</tr>
<tr>
<td>0.67</td>
<td>0.95</td>
<td>0.09</td>
<td>0.87</td>
<td>0.11</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Fig. 3 Typical instantaneous pressure distribution of different turbulence models for 0.5 solidity ratio (A - RKE, B - RNG-86, C - RNG-92 and D - SST)
In general, for all solidity ratios, for windward leg members the evaluated mean drag coefficients using RKE, RNG-92 and SST models are comparable. However, compared to the values evaluated using RNG-86, these values are observed to be more by about 25% for solidity ratio values below 0.5. Whereas, the mean drag coefficients values for leeward leg members are observed to be significantly different from each other of the turbulence models used. This indicates the unique characteristics of the turbulence models in predicting the wake flow behind the windward leg members.

For the solidity ratio of 0.2, the order of magnitude of mean drag coefficient values of all turbulence models is consistent with the expected codal values. It is further found that when the spacing of the objects is large enough (corresponding to solidity ratio of 0.2), the alternate vortices shed from the windward members are fully developed and as result both the windward and leeward leg members are individually behave like an isolated single member. Generally, in such isolated leg member cases, the numerical methods simulate the flow aspects well and obtain good agreement with expected codal values.

For solidity ratios of 0.676 and 0.5, leeward leg members are observed to be located in the wake of windward leg members i.e., angle sections are nearly closer to each other and they represent single square section. The wake characteristics are expected to be similar to those for a single body and vortex shedding is formed by the vorticity generated from the windward members. So, the mean drag coefficient for windward leg members is observed to be significant than that of the leeward leg members for all turbulence models. For these solidity ratio ranges, the trend of numerical prediction on mean drag coefficient values of all turbulence models is in good agreement with the expected codal values (Fig. 2).

Whereas, for solidity ratios of 0.3 and 0.4, mean drag coefficient prediction by using RNG-86, RKE, RNG-92 and SST models are observed to be quantitatively or qualitatively deviated on higher side from the codal values. The mean drag coefficients of windward and leeward leg members of above turbulence models are suppose to decrease than 0.5 solidity ratio case. In contrast, the mean drag coefficient obtained using these turbulence models are increased. This large discrepancy could be attributed to the effect of separated shear layer formed from the windward leg member are not able to reattach on leeward leg member, which is shown in Figures. 4 and 5. The flow for these range of solidity ratio suppose to undergo a transformation from flow on isolated leg member to reattachment of shear layer on the leeward leg member, so that there is no vortex shedding between the windward and leeward leg members. But the prediction of above turbulence models (RKE model, RNG-86, RNG-92 model and SST model) depicts the vortex shedding flow pattern behind the windward leg members similar to isolated leg member case.

In addition, the deviations in the flow pattern prediction are further discussed through the Fourier spectral analysis of lift coefficients of windward leg member for the solidity ratios 0.3 to 0.4 which is shown in Figures.6 and 7. Within the flow transformation region, the vortex shedding peaks in the power spectra is expected to generate multi peak power spectra because of reattachment of shear layers on leeward members. But from the results of Fourier spectral analysis of time varying lift coefficient, it is observed that there is a dominant single peak in the spectra for both solidity ratios. This is quite similar to the vortex shedding flow pattern for isolated leg members. The observed single dominant peak of the power spectra’s is also confirmed the shedding of vortices emerging from the windward leg member does not
reattach to the sides of the leeward leg member. Such a discrepancy in flow pattern prediction leads to poor prediction of mean drag coefficient.

Fig. 4 Typical instantaneous vorticity magnitude contour of different turbulence models for 0.4 solidity ratio (A - RKE, B - RNG-86, C - RNG-92 and D - SST)

Fig. 5 Typical instantaneous vorticity magnitude contour of different turbulence models for 0.3 solidity ratio (A - RKE, B - RNG-86, C - RNG-92 and D - SST)
Fig. 6 Power spectra of lift coefficient of windward leg member for solidity ratio 0.4

Fig. 7 Power spectra of lift coefficient of windward leg member for solidity ratio 0.3
Summary and Conclusions

In the present study, numerical studies on 2-D square lattice tower section have been carried out for different solidity ratio values using various turbulence models, viz. Realizable $k$–$\varepsilon$ model, two versions of RNG $k$–$\varepsilon$ model and SST $k$–$\omega$ model. The numerically evaluated mean drag coefficient values have been compared with those provided in various international codes to assess the relative performance of these turbulence models. The predicted mean drag coefficient using RNG-86 model compared reasonably well with the codal values for all solidity ratios. Further, except for solidity ratio values between 0.3 and 0.4, the predicted mean drag coefficient values using other turbulence models also compared well with the codal values. The deviations in the mean drag coefficient prediction and the numerical limitations are further discussed using local mean drag coefficient values and Fourier analysis of lift coefficients. The deviations in the mean drag coefficient predictions are essentially attributed to the limitations of the two equation turbulence models in predicting the wake flow behind the windward leg members in the flow transformation region. Even though, these two-equation turbulence models are most commonly used in practice, they appear to have certain limitations in predicting the wake flow characteristics. Hence, improvements of the model formulations are required to predict wake flow characteristics.

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References


