Detached Eddy Simulation of Flow around a Box Girder Bridge Section

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ABSTRACT: In this study, detached eddy simulation (DES) based on a modification to the Spalart-Allmaras one equation RANS model is applied to predict aerodynamic characteristics of the flow around a box girder bridge. Single and tandem types of box girder cross sections are treated. One-equation RANS model and LES based on the Smagorinsky model are also used for the same simulation. The improved balancing tensor diffusivity (IBTD) / fractional step (FS) finite element formulation is applied to a computational procedure. Comparing with results of wind tunnel test and other turbulence models, the applicability of DES is examined and the aerodynamic characteristics of each cross section are also discussed.

KEYWORDS: box girder bridge, aerodynamic characteristics, RANS, LES, DES, FEM

1 INTRODUCTION

Wind tunnel tests have traditionally been considered the most reliable method for investigating bridge aerodynamics, even though they are relatively expensive and time-consuming. With the rapid increase in computer efficiency and the recent developments in computational fluid dynamics (CFD), numerical simulation of flows around a bridge deck section has become a cost-efficient and increasingly accurate approach, which is able to integrate the experimental one.

Turbulence model is generally employed to the numerical simulation of flows around a bridge deck section. Two kinds of turbulence models, the Reynolds-averaged Navier-Stokes (RANS) model and the large eddy simulation (LES), are most popular, but recently, the detached eddy simulation (DES) which is a hybrid RANS / LES technique was proposed by Spalart et al. The DES was originally designed for application to massively separated flows. In natural applications of the technique, the DES reduces essentially to prediction of attached boundary layers using a RANS approach and becomes a LES in regions away from the wall where there is sufficient grid density. In this study, the DES is applied to predict aerodynamic characteristics of the flow around a box girder bridge section. Comparing with results of wind tunnel test and CFD, the applicability of DES is examined.

2 METHODOLOGIES

2.1 Governing equations

Assuming that the flow is incompressible, the following incompressible Navier-Stokes equations can be used to describe the flow,

\[ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) - \nabla \cdot \sigma(p, \mathbf{u}) = \mathbf{0} \quad \text{in } \Omega, \]

\[ \nabla \cdot \mathbf{u} = 0 \quad \text{in } \Omega, \]

where \( \rho \) is fluid density, \( \mathbf{u} \) is velocity, \( p \) is pressure and \( \sigma(p, \mathbf{u}) \) is stress tensor.
Considering the turbulence model, variables $u$ and $p$ in equations (1) and (2) are replaced by space filtered or time averaged variables, and stress tensor $\sigma(p, u)$ can be written as,

$$\sigma(p, u) = -\left(p + \frac{2}{5} \rho k_t \right) I + \left(\mu + \rho \nu_t\right) \left(\nabla u + (\nabla u)^T\right),$$

(3)

where $\mu$ and $\nu_t$ are, respectively, molecular and turbulent eddy viscosities and $k_t$ is turbulent energy.

2.2 Detached eddy simulation

The DES formulation in this study is based on a modification to the Spalart-Allmaras (SA) one equation RANS model such that it reduces to RANS close to the wall and to LES away from the wall. The SA RANS model is written as,

$$\frac{D\tilde{\nu}}{Dt} = c_{b1} \tilde{S} \tilde{\nu} + \frac{1}{\sigma} \left[ \nabla \cdot (\nu + \tilde{\nu} \nabla \tilde{\nu}) + c_{b2} (\nabla \tilde{\nu})^2 \right] - c_{w1} f_w \left[ \frac{\tilde{\nu}}{d} \right]^2$$

(4)

where $\tilde{\nu}$ is the working variable. For a detailed explanation of each term, see 1). The turbulent eddy viscosity $\nu_t$ is obtained from a function of $\tilde{\nu}$.

The DES formulation is obtained by replacing the distance to the nearest wall $d$ by $\tilde{d}$ is defined as,

$$\tilde{d} = \min(d, C_{DES}\Delta),$$

(5)

where $C_{DES}$ is a constant, and $\Delta$ is local measure of element size.

2.3 Computational procedure

In this study, the improved balancing tensor diffusivity (IBTD) / fractional step (FS) formulation 2) based on the finite element method is applied. the present formulation can be obtained from simplifying the stabilized finite element formulation 3). The equal order interpolation is used for velocity and pressure elements. The bi- or tri-linear interpolation function is used. In the present formulation, the linear equation system matrices for momentum and continuity equations become symmetric. It is possible to compute only using the symmetric solver, the diagonal scaling Conjugate Gradient (SCG) method is used for solving the linear equation system.

3 COMPUTATIONAL CONDITIONS

Single and tandem types of box girder bridge cross sections which are shown in Figure 1 are investigated in this study. The aerodynamic characteristics of these cross sections were experimented by Watanabe et al.4). Figure 1(a) shows single type cross section including regular triangle type fairing with side ratio of $B/D = 12$, and figure 1(b) shows tandem type cross section with opening spacing of $4D$.

Three kinds of turbulence models which are RANS (S-A model), LES based on Smagorinsky model at $C_s = 0.13$ and DES are applied. The parameter $C_{DES}$ is set $C_{DES} = 0.42$ which is smaller than original model $C_{DES} = 0.65$ 1). The element size $\Delta$ is set $\Delta = \max(\Delta x, \Delta y)$, where $\Delta x$ and $\Delta y$ are local element lengths in the 2-D plane. 2-D computation is enough for RANS, but LES and DES need 3-D computation. Figures 2 and 3 show the finite element mesh in 2-D plane and the domain of tandem type. The total number of elements of tandem type is 48,106. The length of span-wise direction is $6.4D$ and divided into 64 equal layers. The total number of elements for 3-D computation is 3,079,784.
Reynolds number is defined as \( R_e = \frac{\rho UD}{\mu} = 5.0 \times 10^4 \). The angle of attack is set two cases \( \alpha = 0^\circ, 1^\circ \) to obtain gradient of fluid forces. The time increment is \( \Delta t = 0.05D/U \) and the minimum element length in the wall-normal direction is 0.0005D.

![Figure 1. Box girder bridge cross sections](image1)

![Figure 2. Finite element mesh in 2-D plane](image2)

![Figure 3. Domain](image3)

4 RESULTS AND DISCUSSIONS

4.1 Element length in wall units

Figure 4 shows each element length in wall units which is defined as \( \Delta i^+ = u_r \Delta i/\nu \), where \( u_r \) is friction velocity. In the wall-parallel direction, \( \Delta x^+ \) is 50 ~ 250, it is large compared to the required element length for the LES. In case of the DES, the element length in the wall-parallel direction can be set large because the wall boundary layer is solved by the RANS. In the wall-normal direction, the first spacing is decided by the RANS model, about \( \Delta y^+ = 2 \) or less. In the case, \( \Delta y^+ \) is about 1. In the span-wise direction, \( \Delta z^+ \) is about 250, it is also large compared to the required element length for the LES. In case of the LES calculation, the element lengths near the wall boundary layer are not detailed enough.

![Figure 4. Element length in wall units](image4)

4.2 Fluid force coefficients

Comparison between the present computed results and the experimental results reported by Watanabe et al.\(^4\) is shown in Figure 5. In case of the single type, computed results by three turbulence
models are in agreement with each other and experimental results. In case of the tandem type, the RANS result on gradient of lift and momentum coefficients does not correspond to experimental result, however, the LES and DES results agree well with the experimental results. In addition, the DES result approaches the experimental result further more.

![Comparison of three components of fluid force coefficients](image)

Figure 5. Comparison of three components of fluid force coefficients

4.3 Flow field

Figure 6 shows the bird’s-eye view of instantaneous vorticities \( \omega_z = \pm 1 \). Complex three dimensionalities of the flow are caused by the DES result as well as the LES result.

![Bird’s-eye view of instantaneous vorticities](image)

Figure 6. Bird’s-eye view of instantaneous vorticities \( \omega_z = \pm 1 \) (\( \alpha = 0^\circ \))

5 CONCLUSION

The detached eddy simulation (DES) was performed for the flow around single and tandem type box girder bridge sections. Comparing with results of RANS, LES and DES, the applicability of DES could be examined for bridge aerodynamics.

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