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5 1 **Strategies for modeling homogeneous isotropic turbulence and**
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7 2 **investigation of spatially correlated aerodynamic forces on a**
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9 3 **stationary model**
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20 8 **Abstract:** A numerical simulation method is proposed for the generation of
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22 9 homogeneous isotropic turbulence and is applied to the investigation of the spanwise
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24 10 coherence aerodynamic force on a stationary airfoil. First, the inflow turbulence is
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26 11 generated by modeling a grid at the inlet of the computational domain. To verify the
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28 12 accuracy of the generated turbulence field, a series of relevant parameters are
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30 13 compared with the results of wind tunnel tests and previous studies. A model with
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32 14 NACA 0015 profile is then placed in the downstream turbulence. The relationship
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34 15 between the spanwise correlation width of the vertical turbulence component and the
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36 16 lift force is determined. Possible mechanisms for the result are discussed. This study
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38 17 demonstrates that the proposed turbulence generation method is an effective tool for
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40 18 investigating the spatial distribution of unsteady aerodynamic loads on elongated
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42 19 bodies.
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49 20 **Keywords:** Numerical simulation; grid-generated turbulence; spatial distribution;
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51 21 aerodynamic force.
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63 **1. Introduction**
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66 24 Almost all previous studies of spatially correlated aerodynamic forces on bodies
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68 25 immersed in turbulent flow have involved wind tunnel tests or theoretical analyses. In
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71 26 contrast to these approaches, numerical methods have the advantage of providing
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74 27 abundant detailed data at low cost. In recent years, with the rapid development of both
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76 28 computational fluid dynamics (CFD) techniques and computer hardware, several
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78 29 numerical methods for generating turbulence using large eddy simulation (LES) have
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81 30 been proposed to model the characteristics of real fluid flows. The generation of
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83 31 turbulence by CFD software has great potential for the investigation of the three-
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85 32 dimensional characteristics of aerodynamic forces.
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88 33 For accurate simulation of aerodynamic forces on bodies immersed in turbulent flows,
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91 34 the generated turbulence field must, like a real flow, be spatially correlated and
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93 35 evolved. Also, for engineering application, the turbulence parameters must be easily
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95 36 modified. There are two main methods for generating homogenous isotropic
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97 37 turbulence at the inlet of the computational domain using LES: precursor simulation
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100 38 (Spalart, 1986, 1988; Pierce and Moin, 1998; Schlüter and Moin, 2004; Jiang, et al.,
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102 39 2012) and the synthesis method (Lee et al., 1992; Kondo et al., 1997; Mathey et al.,
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104 40 2006; Huang et al., 2010). The two methods have been reviewed in detail by Liu and
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107 41 Pletcher (2006), Tabor (2010), and Dhamankar (2015). Both methods specify the
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110 42 statistical data character of instantaneous turbulence as part of the inlet boundary
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112 43 conditions. **Synthesis methods are convenient to specify the parameters of the inlet**
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114 44 **turbulence, but they are inherently inaccurate and the provision of an inlet**
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122 45 development section is required. In contrast, precursor simulation methods generate
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124 46 true turbulence that is inherently more accurate, however can be cumbersome to
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127 47 generate the turbulence of required characteristics. In this study, a method of directly
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129 48 modeling the grid at the inlet to generate spatially correlated and evolved turbulence
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132 49 is proposed. The advantage of this grid-generated turbulence method is the generation
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134 50 of inherently accurate turbulence that allows easy comparison with wind tunnel tests;
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136 51 as well, the turbulence characteristics can be modified conveniently by changing the
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139 52 size of the grid.

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142 53 In the study of unsteady aerodynamic loading on elongated bodies in turbulent flows,
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144 54 one of the fundamental assumptions is the strip assumption, according to which the
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147 55 spatial distribution of unsteady aerodynamic loading can be represented by oncoming
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149 56 transversely fully coherent gusts (Fung, 1955). This assumption had been widely
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152 57 adopted in wind loading codes and standards. However, as first observed by Nettleton
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154 58 (see Ektin, 1971), the lift force on an airfoil is more strongly correlated than the
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157 59 fluctuation components when the turbulence scale is smaller than or similar to the
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159 60 chordwise dimension of the airfoil, thus invalidating the strip assumption. Nettleton's
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161 61 finding has been confirmed by wind tunnel tests relating to the lift force on a bluff
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164 62 body (Sankaran and Jancauskas, 1993; Jakobsen, 1997; Kimura et al., 1997; Larose,
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166 63 1997; Li, 2015).

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169 64 All previous research on this topic involved either theoretical analysis or wind tunnel
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171 65 tests, whereas, in the present study, the relationship between vertical velocity
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174 66 fluctuations and unsteady aerodynamic loading is investigated through CFD
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181 67 simulations. First, a grid is modeled at the inlet of the computational domain to
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183 68 generate homogeneous isotropic turbulence, using three-dimensional LES. After
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186 69 verification of the simulation results by comparison with the results of wind tunnel
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188 70 tests and previous studies, a stationary model of a section of the NACA 0015 airfoil is
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191 71 chosen to study the spatial correlation of aerodynamic forces. A relationship between
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193 72 the spanwise correlation width of the vertical velocity fluctuation and the lift force is
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195 73 obtained and an argument regarding the strip assumption is presented. Finally, the
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198 74 results are discussed.

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201 75 It should be emphasized that the spanwise correlation width of the vertical velocity
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203 76 component and the lift force, which are obtained primarily by numerical methods in
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205 77 this study, are essential for further investigations such as identification of the three-
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208 78 dimensional aerodynamic admittance of elongated bodies like the decks of long-span
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211 79 bridges.

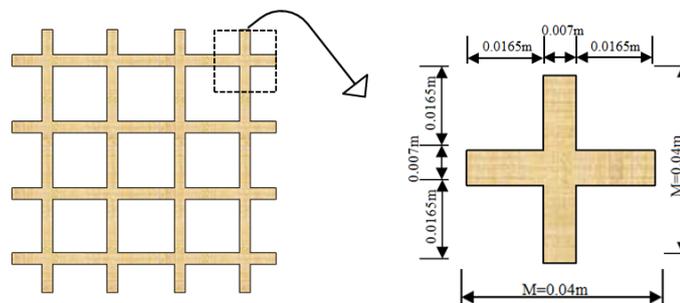
212 213 80 **2. Turbulence generation method**

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216 81 The grid-generated turbulence is produced by modeling a pattern of solid patches at
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218 82 the inlet of the computational domain as in the wind tunnel test. Fig. 1 shows the
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221 83 setup of the inlet grid pattern in this study. Four inlet grids are used to generate
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223 84 turbulence. An inlet grid size $M = 0.04$ m and a bar size of 0.007 m are chosen to
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226 85 facilitate comparison with the wind tunnel test results of [Li \(2015\)](#) to verify the
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228 86 accuracy of the simulation results. The dimension of the computational domain is
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231 87 scaled down by a factor of 10 compared with experiment. This scaling is a balance
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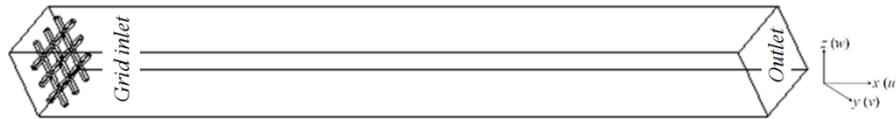
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 240 88 between the two factors. On the one hand, a small mesh size is required to capture the
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 242 89 small-scale vortices to allow investigation of the influence of high-frequency
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 245 90 turbulent fluctuations on the aerodynamic force on the structure. On the other hand, if
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 247 91 the mesh is too fine, then computational efficiency will be poor or computational
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 250 92 capabilities will be exceeded. With this scaling, it is possible to achieve a consistent
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 252 93 influence of turbulence on bodies in the simulations and in the wind tunnel tests by
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 254 94 choosing the same Reynolds number, while also improving the computational
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 257 95 efficiency. The experiments are described in Section 3.

260 96 The computational domain is shown in Fig. 2. Both the height and width of the
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 262 97 domain are $4M$ and the length is $60M$. This length is chosen to allow investigation of
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 264 98 the development of the turbulence field and the relationship among the various
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 267 99 parameters involved. The CFD simulations are described in Section 4 and the
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 269 100 validation of the generated turbulence field is described in Section 5.

272 101 The proposed method can be used to study the aerodynamic characteristics of a body
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 274 102 by placing it in the nearly isotropic and homogenous region downstream of the inlet.
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 277 103 The use of this method to investigate the spanwise coherence characteristics of the
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 279 104 aerodynamic force on a body is described in Section 6.



282 105
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 287 110 **Fig. 1.** Grid inlet.



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112 **Fig. 2.** Computational domain.

113 **3. Experimental setting**

114 A wind tunnel test conducted by [Li \(2015\)](#) is chosen to verify the numerical
 115 simulation method proposed in this study. The experiment was carried out in the high-
 116 wind-speed test section of the XNJD-1 wind tunnel at Southwest Jiaotong University.

117 A uniform grid was placed at the inlet to produce a homogeneous isotropic turbulence
 118 field (Fig. 3). The grid aperture was 0.33 m and the bar size was 0.07 m. The inlet
 119 grid consists of $4 \times 4 = 16$ grid patterns. The turbulent fluctuations were measured
 120 simultaneously in the streamwise, spanwise, and vertical directions by a Cobra Probe
 121 downstream at the position where the model airfoil to be investigated would be
 122 placed. The turbulence integral scale and turbulence intensity in the three directions at
 123 the model location are shown in Table 1.

124 Fig. 4 compares the experimental results for the spanwise correlation coefficients of
 125 the vertical fluctuation component with the theoretical results of [Bullen \(1961\)](#). It can
 126 be seen that the measured correlation coefficients of the vertical velocity fluctuation
 127 are in agreement with Bullen's results, which means that the turbulence generated in
 128 the wind tunnel test satisfies the assumption of homogeneity and isotropy. The test
 129 results are thus highly reliable and can be used for comparison.

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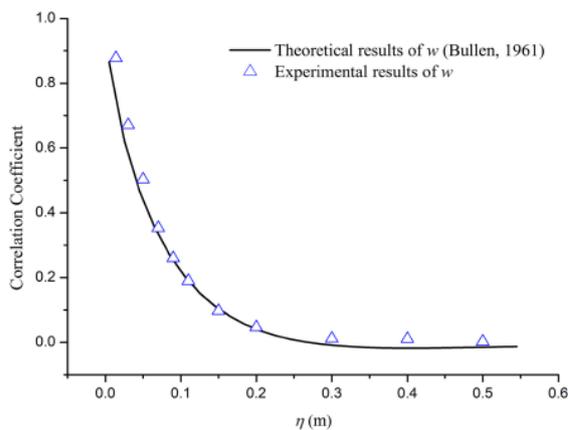
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131 **Fig. 3.** Wind tunnel test of Li (2015).

132 **Table 1** Parameters of grid-generated turbulence in wind tunnel test.

Turbulence integral scale			Turbulence intensity		
L_u (m)	L_v (m)	L_w (m)	I_u (%)	I_v (%)	I_w (%)
0.107	0.042	0.054	8.0	6.1	6.5

133 Note: L_u , L_v , and L_w are the streamwise, spanwise, and vertical integral scales,
 134 respectively; I_u , I_v , and I_w are the streamwise, spanwise, and vertical turbulence
 135 intensities, respectively.



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137 **Fig. 4.** Spanwise correlation coefficients of w : comparison between experimental
 138 results and Bullen's theoretical results (After Li, 2015).

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417 **139 4 Numerical methods**
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420 **140 4.1 Turbulence modeling and solver setting**
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423 **141 In this study, a three-dimensional incompressible fluid motion is described using LES,**
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425 **142 in which the large-scale turbulence is resolved while small-scale turbulence is**
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427 **143 modeled.** The commercial CFD code FLUENT 6.3 is adopted to solve the fluid
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429 governing equations of LES. The filtered unsteady Navier–Stokes equations are as
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433 **144 follows:**
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436 **146**
$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

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439 **147**
$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\nu + \nu_{SGS}) \frac{\partial \bar{u}_i}{\partial x_j} \right] \quad (2)$$

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442 **148** where \bar{u}_i ($i = 1, 2, 3$) are the velocity components in the three coordinate directions,
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444 **149** x_i ($i = 1, 2, 3$) are the displacements in these three directions, ρ and p are the air
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446 **150** density and pressure, ν is the kinematic viscosity, ν_{SGS} is the subgrid-scale viscosity,
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448 **151** and the overbar indicates spatially filtered components.
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452 **152** A filter function is used to split the turbulent flow into subgrid-scale (SGS) and grid-
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454 **153** scale (GS) components. The Smagorinsky model is adopted to describe the SGS
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456 **154** stresses between the GS and SGS eddies. The filter function and the Smagorinsky
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458 **155** model are given by
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462 **156**
$$\nu_{SGS} = (C_S \Delta)^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}} \quad (3)$$

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465 **157**
$$\bar{S}_{ij} = \frac{1}{2} \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (4)$$

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467 **158** where ν_{SGS} is the SGS eddy viscosity, \bar{S}_{ij} is the strain rate tensor, $\Delta = \sqrt[3]{\Delta x \Delta y \Delta z}$ is
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476 159 the grid filter width and C_S is the Smagorinsky constant coefficient.
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479 160 In the present investigation, the value of Smagorinsky constant is taken as $C_S = 0.1$,
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481 161 which is an appropriate value for the simulation of bodies immersed in turbulent flow
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484 162 (Liang and Papadakis, 2007). The FLUENT code is based on the finite-volume
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486 163 method (FVM), which defines the pressure and velocity at the centers of the control
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488 164 volumes and the volume fluxes at the midpoints of the cell surfaces. The well-known
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491 165 PISO (pressure implicit with splitting of operators) algorithm proposed by Issa (1986)
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493 166 is used for the pressure-velocity coupling procedure between the momentum and
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496 167 continuity equations. A fully implicit second-order time-advancement scheme is used
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498 168 for temporal discretization to reduce numerical diffusion. To obtain an accurate
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501 169 simulation, a second-order central differencing scheme is chosen for spatial
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503 170 discretization.

504 505 506 171 **4.2 Computational domain and boundary conditions**

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509 172 The geometry of the grid and domain configurations is as shown in Section 2. The
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511 173 computational domain has dimensions of 0.16 m (width) \times 0.16 m (height) \times 2.4 m
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513 174 (length), where the width and height are scaled down from the wind tunnel cross-
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516 175 section by a factor of 10.

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519 176 The velocity inlet condition is applied at the inlet boundary with an oncoming flow
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521 177 velocity of 11.5 m/s, which coincides with that of the wind tunnel test. At the outflow
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523 178 boundary, a convection boundary condition is applied for the velocity and a
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526 179 Neumann-type condition for the pseudo-pressure. A no-slip boundary condition ($u = v$
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535 180 = $w = 0$) is imposed at the wall and on the grid surface, which again is similar to the
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537 181 conditions in the wind tunnel experiment.
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540 182 **4.3 Grid-independence test**

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543 183 The accuracy of the computational simulation results depends strongly on the cell
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545 184 numbers and mesh size, and so the grid-independence test is extremely important.
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548 185 Given the simplicity of the model structure, hexahedral cells are employed in the
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550 186 simulation to obtain stable algorithms and accurate account of viscous effects. Small
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552 187 mesh size is required to capture the small-scale vortices. However, an excessive
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554 188 number of cells will reduce computational efficiency. To test the influence of mesh
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556 189 size, the turbulence intensity and spanwise correlation relationship of vertical
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558 190 turbulence are compared with Li's wind tunnel test results. The mesh sizes are
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560 191 uniformly spaced along the streamwise, spanwise, and vertical directions. Three mesh
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562 192 sizes are tested: 0.00625 m, 0.003125 m, and 0.001875 m. The velocity data of 10
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564 193 seconds physical time is used in order to have a long enough statistical sample to
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566 194 obtain the spanwise correlation coefficient. Computations are carried out on 8 Intel
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568 195 Core i7-7820X 3.6GHz CUPs with 16 threads parallel computing. The maximum of
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570 196 about 16 G of RAM memory is required. The number of cells and calculation time of
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572 197 the three cases are specified in Table 2.
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200 **Table 2** Number of cells and computational time

Case	Mesh size (m)	Number of cells (million)	Computational time (days)
1	0.00625	0.92	1
2	0.003125	3.59	4
3	0.001875	10.69	11

201 Comparisons of turbulence intensity components are shown in Table 3. In general, the
 202 results of I components in all three cases are in good agreement with those of the wind
 203 tunnel test. The accuracy improves with decreasing the cells size. There is a large
 204 deviation of case 1 but that of cases 2 and 3 is relatively small, although there is a
 205 higher discrepancy for the prediction of the spanwise turbulence intensity with case 3
 206 than with case 2 which however involves a coarser mesh. This may be due to the error
 207 of wind tunnel experiment.

208 **Table 3** Grid-independence test of turbulence intensity.

Case	Mesh size (m)	I_u (%)	I_v (%)	I_w (%)	Deviation in	Deviation in	Deviation in
					I_u (%)	I_v (%)	I_w (%)
1	0.00625	7.51	6.52	5.92	6.13	6.89	8.92
2	0.003125	7.85	6.16	6.22	1.88	0.98	4.31
3	0.001875	7.96	5.96	6.33	0.50	2.30	2.62

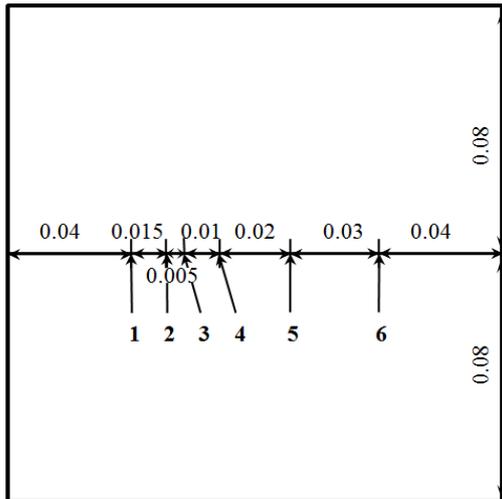
209 The relationships among L components in the streamwise, spanwise, and vertical
 210 directions are important criteria to test the authenticity of homogeneous isotropic
 211 turbulence fields. The results are shown in Table 4. Again, the results improve with
 212 the decreasing of mesh size. However, agreement is less satisfactory for the

213 relationships among the L components, with the coefficients of proportionality
 214 obtained by numerical simulation being somewhat higher than those from the wind
 215 tunnel test: by 11% - 17% for the relationship between the vertical and streamwise
 216 components and as much as 27% - 34% for that between the spanwise and streamwise
 217 components. This latter deviation may be due to experimental error since the value of
 218 L_v obtained by wind tunnel test is relatively small compared with theoretical value.

219 **Table 4** Grid-independence test of turbulence integral length-scale.

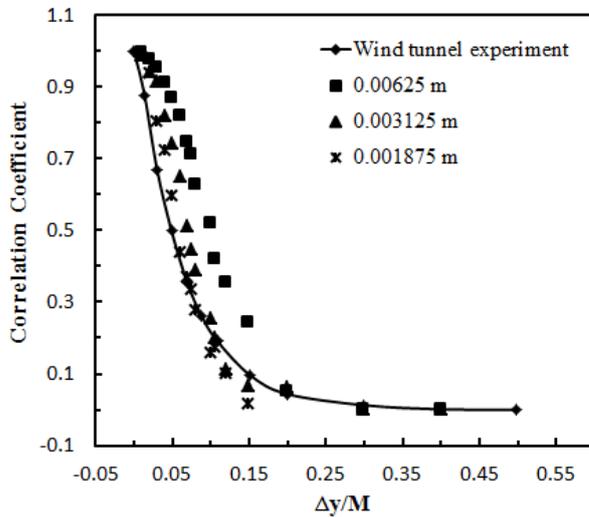
Case	Mesh size (m)	L_v/L_u	L_w/L_u	Deviation in L_v/L_u	Deviation in L_w/L_u
1	0.00625	0.528	0.594	34%	17%
2	0.003125	0.505	0.578	28%	14%
3	0.001875	0.497	0.561	27%	11%

220 Six observation points with uneven spacing, as shown in Fig. 5, are chosen at the
 221 central line of the cross section 45 M downstream of the inlet grid to determine the
 222 correlations among vertical turbulence fluctuations. A comparison of the spanwise
 223 correlation results of numerical simulation with those of the wind tunnel test is shown
 224 in Fig. 6. The result improves with the refinement of the mesh, cases 2 and 3 are both
 225 consistent with the wind tunnel test result, while the coefficients in case 1 are slightly
 226 higher than the test result at smaller distances.



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228 **Fig. 5** Distribution of observation points – distances are in meters



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230 **Fig. 6.** Grid-independence test of the spanwise relationship.

231 On the basis of the grid-independence test, a cell size of 0.003125 m is adopted to
 232 capture the turbulent field characteristics adequately while saving computational time.

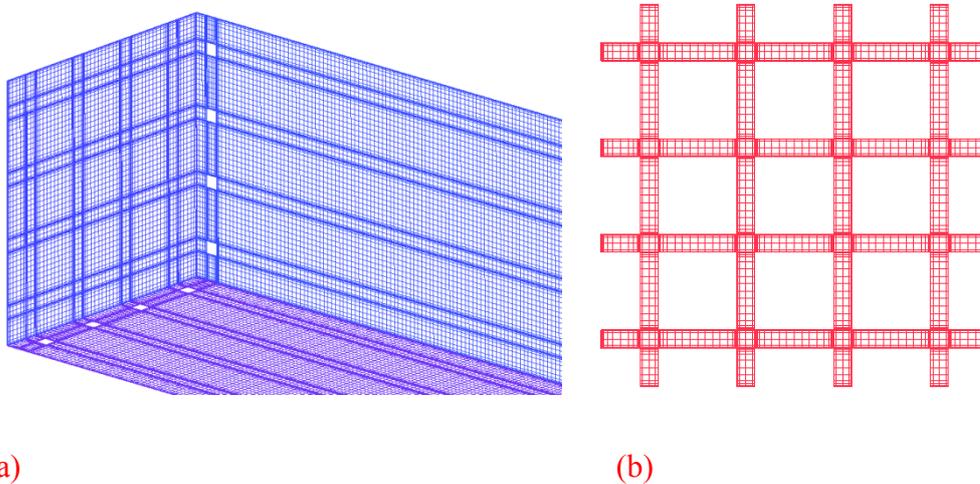
233 The mesh distribution is shown in Fig. 7. The first layer of mesh size near the surface
 234 of the grid is 0.00003 m, with corresponding values of $y^+ \leq 1$. **The wall – resolved**

235 **LES is adopted to obtain an accurate simulation of the boundary layer. The high**

236 **aspect ratio is avoided by scaling down the computational domain size and increasing**

237 **the cells number. The dimensionless cell sizes of the model surface are $\overline{\Delta x^+} = 41$,**

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771 238 $\overline{\Delta y^+} = 80$, where x and y are streamwise and spanwise respectively. It is worth
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773 239 pointing out that these values are larger than those suggested for wall-resolved LES,
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775 240 namely $\Delta x^+ = 100$, $\Delta y^+ = 20$ by Chapman (1979) and $\Delta x^+ = 50 \sim 130$ and Δy^+
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778 241 $= 15 \sim 30$ by Choi and Moin (2012). However the adopted mesh generation strategy
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780 242 permits to achieve a sufficiently good result with an overall cells number of about
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783 243 3.59×10^6 .



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802 246 **Fig. 7.** Computational mesh distribution: (a) computational domain; (b) mesh of inlet
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804 247 grid.

807 248 5. Validation of turbulence field

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810 249 In order to demonstrate that the proposed turbulence generation method can be used
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812 250 effectively to investigate the aerodynamic characteristics of structures, the turbulence
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815 251 should satisfy the following conditions:

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818 252 (1) the development of vortex structures should exhibit behavior like that of real grid-
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820 253 generated turbulence;

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830 254 (2) a series of relevant turbulence parameters should be validated to ensure that a
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832 255 nearly homogeneous isotropic region is obtained downstream.

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835 256 In this section, a series of relevant turbulence parameters are compared with wind
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838 257 tunnel results and the results of previous studies to verify the accuracy of the
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840 258 numerical simulation results. The parameters to be verified are the power-law
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845 260 density, and the spatial correlation relationships of the turbulence.

847 848 261 **5.1 Power-law relationship**

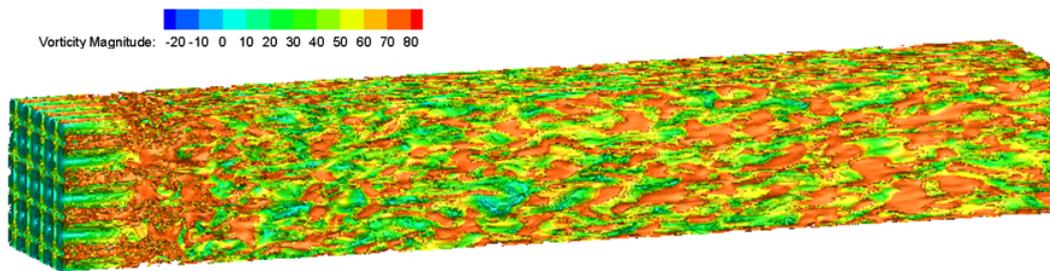
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851 262 The instantaneous vortex structures of the turbulence field generated by numerical
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853 263 methods are shown in Fig. 8. A deeper insight into the structure of the turbulent flow
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855 264 in the interior of the domain can be obtained from Figs. 9 and 10. Fig. 9 displays the
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858 265 magnitude of the vorticity in an xz cutting plane in the middle of the simulation
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860 266 domain ($y = 2 M$), while Fig. 10 displays the magnitude of the vorticity in yz cutting
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863 267 planes (i.e., planes parallel to the grid) at distances $x = 5 M, 10 M, 15 M, 20 M, 25 M,$
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865 268 $30 M, 35 M,$ and $40 M$ downstream of the computational domain.

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868 269 It can be seen that the development of the turbulence field downstream of the inlet is
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870 270 identical to the description of a wind tunnel result given by [Monin and Yaglon \(1975\)](#),
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873 271 who proposed that the turbulence field downstream of a grid can be divided into three
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875 272 regions. The first region, which is next to the grid, is called the developing region.
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878 273 The vorticity is generated at the grid of the inflow boundary and develops into the
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880 274 domain from there. This region consists mainly of the grid wakes. It can be seen
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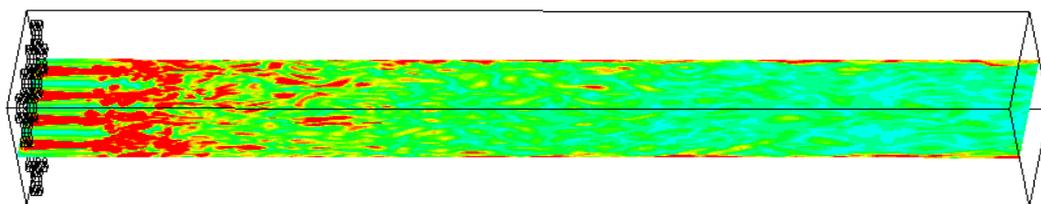
275 clearly from Fig. 1 (a–d) that the flow is non-homogeneous and anisotropic.

276 The turbulence gradually become homogenous and isotropic as the flow proceeds
277 downstream, as can be seen from Fig. 10 (e-h), although there is apparently energy
278 transfer between wavenumbers. In the near-wall region, the turbulence develops into
279 elongated streamwise structures, while more homogeneous, isotropic turbulence is
280 generated away from the wall. Aerodynamic effects on bodies immersed in a
281 turbulent flow are usually investigated in this region. This region is followed by the
282 developed region which is the final period of decay. Figures 8–10 demonstrate that
283 the method presented here enables simulation of more realistic flow structures.



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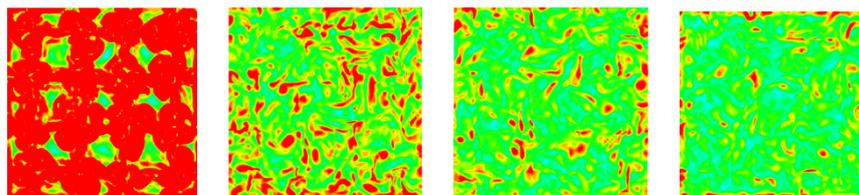
285 **Fig. 8.** Development of instantaneous vortex structures.



286

287 **Fig. 9.** Contours of instantaneous vorticity in the xz plane at $y = 2 M$.

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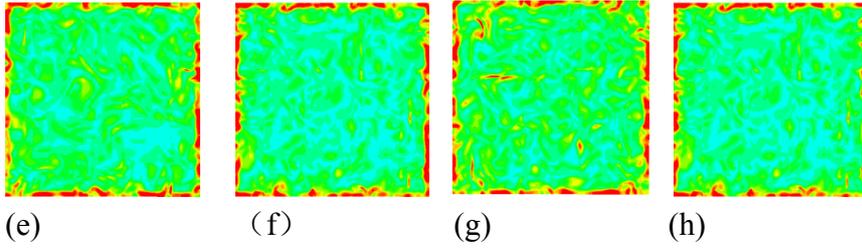
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(a)

(b)

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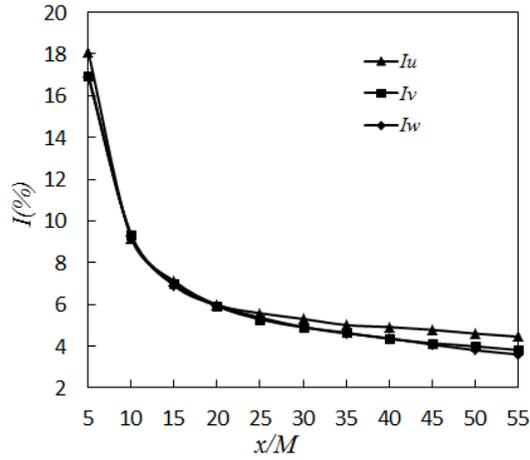
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293 **Fig. 10.** Contours of instantaneous vorticity in yz planes at (a) $x = 5 M$; (b) $x = 10 M$;
294 (c) $x = 15 M$; (d) $x = 20 M$; (e) $x = 25 M$; (f) $x = 30 M$; (g) $x = 35 M$; (h) $x = 40 M$.

295 The second region is also called the power-law region, where the decay rate of the
296 turbulence intensity and the growth rate of the integral length both obey power laws.

297 The exponents in these power laws are independent of Reynolds number, grid
298 solidity, rod shape, and mesh size. In a pioneering paper, [Taylor \(1935b\)](#) proposed
299 that the turbulence downstream is statistically homogeneous and approximately
300 isotropic in the power-law region, which is 40 – 50 times the grid length downstream
301 of the grid inlet. It was also suggested by [Corrsin \(1963\)](#) that homogeneity conditions
302 are satisfied at $x/M \geq 40$ for grids with relatively low solidity. In this study, the data
303 from $x/M = 40$ to $x/M = 55$ are used to determine the power-law exponents for the
304 variation of relevant parameters with distance. A series of monitoring points are
305 located on the central line of the computational domain in the streamwise direction to
306 observe the velocity fluctuations.

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308 **Fig. 11.** Development of turbulence intensity with distance from grid inlet.

309 The development of the turbulence intensity with the distance from the grid inlet is
 310 shown in Fig. 11. It can be seen that the intensity falls dramatically from its original
 311 value until about 30 M downstream of the grid inlet, after which the decrease becomes
 312 more gradual between 35 M and 55 M , which is the nearly homogenous and isotropic
 313 region. A decay power law proposed by [Mohamed and LaRue \(1990\)](#) is used to
 314 determine the value of the exponent in this investigation, which is based on Taylor's
 315 hypothesis:

316
$$\frac{u'^2}{U^2} = I^2 = A \left(\frac{x}{M} - \frac{x_0}{M} \right)^{-n} \quad (5)$$

317 where u' is the resolved velocity fluctuation in the streamwise direction, U is the
 318 mean velocity, A is a constant called the decay coefficient, x is the positive distance
 319 downstream of the grid, x_0 is the virtual origin, and n is the decay exponent.

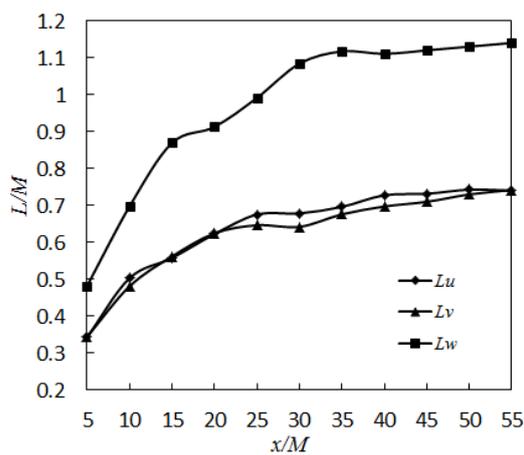
320 The decay exponent of the turbulence intensity is found by the numerical method to
 321 be $1.09 < n < 1.26$ when the virtual origin is taken to be zero. For comparison, the
 322 predictions for the decay exponent by [von Kármán and Howarth \(1938\)](#), [Kolmogorov](#)

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 1066 323 (1941), Saffman (1967), and Mohamed and LaRue (1990) are 1, 1.43, 1.2, and 1.33,
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 1068 324 respectively.

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 1071 325 Another important parameter is the growth exponent for the integral length-scale.
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 1073 326 With the development of the turbulence field, the integral length-scale first
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 1075 327 experiences a sharp rise, followed by a more gradual increase as the distance
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 1077 328 downstream of the grid increases, as displayed in Fig. 12. The power-law relationship
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 1079 329 is

$$L = B \left(\frac{x - x_0}{M} \right)^m \quad (6)$$

1082
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 1084 330 where B is a constant and m is the growth exponent of the length-scale. According to
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 1086 331 the proposed method, the growth rate in Eq. (6) is $0.376 < m < 0.421$, which
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 1088 332 corresponds very closely to the values of $m = 0.36$ found by Davidson and Krogstad
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 1090 333 (2009) and $m \approx 0.4$ found by Krogstad and Davidson (2011).
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 1111 336 **Fig. 12.** Development of integral length-scale with distance from grid inlet.

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 1114 337 In conclusion, the development of the turbulence intensity and integral length-scale of
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 1116 338 the generated turbulence field both satisfy power-law relationships. These results

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1125 339 demonstrate that the region used to investigate aerodynamic effects on immersed
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1128 340 structures meets the condition of a nearly homogeneous and isotropic turbulence field.
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1130 341 **5.2 Turbulence spectrum**

1133 342 It is of great importance that the spectrum of the generated turbulence satisfies the von
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1136 343 Kármán model (Simiu and Scanlan, 1996), since this model has been found to be
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1138 344 appropriate for the real turbulence spectrum in the atmospheric boundary layer
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1141 345 (Lumley and Panofsky, 1964; Hinze, 1975; Li et al., 2007) as well as for the
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1143 346 homogeneous isotropic turbulence generated by a uniform grid (Robert and Surry,
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1146 347 1973). The spectral densities in the streamwise, spanwise, and vertical directions at
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1148 348 the modeling position are shown in Fig. 13. The spectral densities of the generated
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1150 349 turbulence are depicted well by the von Kármán spectral model, as expressed by the
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1152 350 following equations:

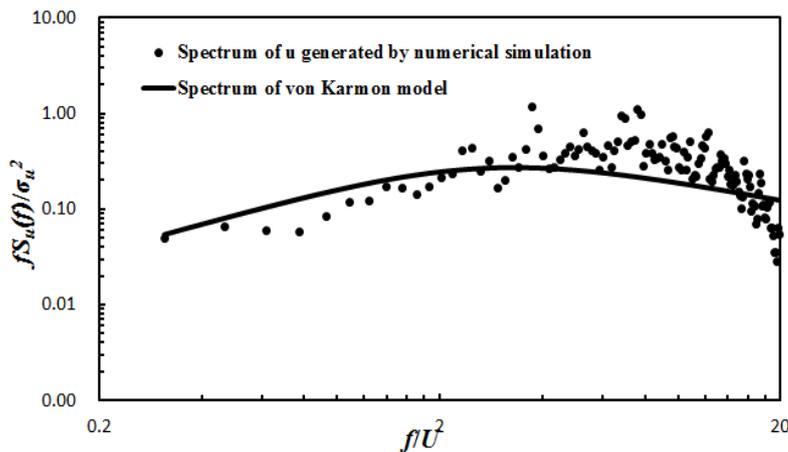
$$1155 \quad \frac{fS_u(f)}{\sigma_u^2} = \frac{4\left(\frac{fL_u}{U}\right)}{\left[1 + 70.8\left(\frac{fL_u}{U}\right)^2\right]^{5/6}} \quad (7a)$$

$$1161 \quad \frac{fS_i(f)}{\sigma_i^2} = \frac{4\left(\frac{fL_i}{U}\right)\left[1 + 755\left(\frac{fL_i}{U}\right)^2\right]}{\left[1 + 238\left(\frac{fL_i}{U}\right)^2\right]^{11/6}} \quad (i = v, w) \quad (7b)$$

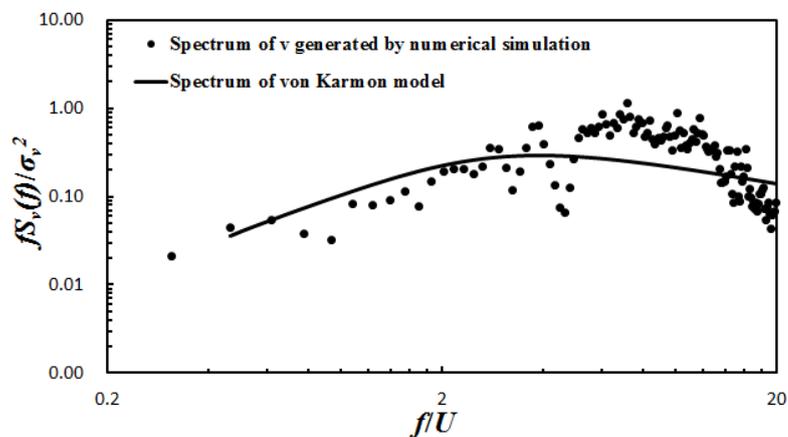
1167
1168 353 where f is the turbulence frequency in the streamwise direction, $S_u(f)$, $S_v(f)$, and
1169
1170 354 $S_w(f)$ are the spectra of the fluctuations in the streamwise, spanwise, and vertical
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1172 355 directions, respectively, and σ_u , σ_v , and σ_w are the variances of these fluctuations.
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1175 356 As can be seen from Fig. 13, the energy-containing subrange of the turbulence
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 1184 357 matches well with the von Kármán spectrum model, but the high-frequency part of the
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 1186 358 inertial subrange and the dissipation subrange are missing. This is a consequence of
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 1189 359 the characteristics of the LES turbulence model. Eddies with a length-scale greater
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 1191 360 than the cutoff width are resolved, while smaller turbulent eddies with high
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 1193 361 frequencies are destroyed and must be described by an SGS model. There will,
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 1195 362 therefore, be a filter cutoff frequency, which is the point at which the spectral curve
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 1197 363 deviates from the $-5/3$ exponent. It can be seen from Fig. 12 that the cutoff frequency
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 1199 364 in this investigation is about 400 Hz and higher frequencies are no longer resolved. It
 1200
 1201 365 should be noted that the absence of higher frequencies does not influence the
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 1203 366 aerodynamic forces to be studied further on in this investigation.



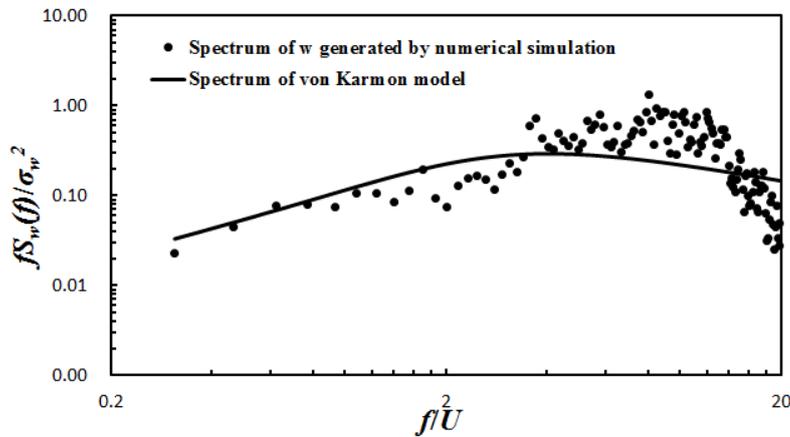
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368 (a)



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(b)



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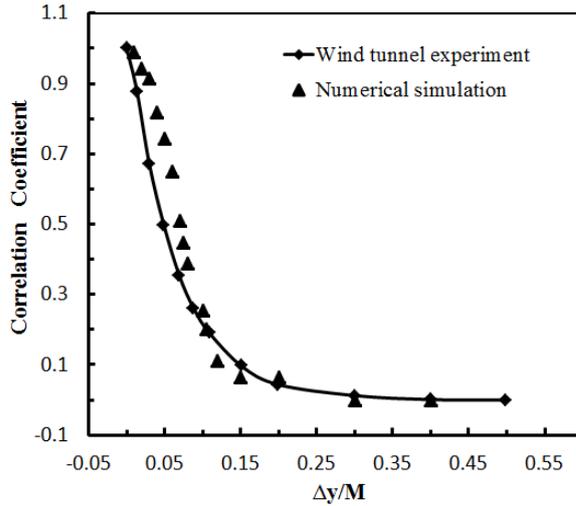
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(c)

373 **Fig. 13.** Comparisons of spectrum density generated by numerical simulation and von
1262 Kármán model: (a) streamwise direction; (b) spanwise direction; (c) vertical direction.

375 5.3 Spatial correlations

376 Accurate simulation of spatial correlations is essential in order to provide a correct
377 representation of the self-preservation of the turbulent flow, as well as for
378 investigation of the buffeting lift on bodies immersed in the flow field. Correlation
379 curves from the numerical simulation and the wind tunnel test are shown in Fig. 14. It
380 can be seen that the numerical results correspond well to those from the wind tunnel
381 test, although they do not match precisely. The rate at which the vertical turbulence
382 fluctuation correlation coefficients decrease with distance is somewhat faster in the
383 numerical results than in the experimental results, which means that the generated
384 turbulence is more spatially correlated. This may be due to the scaling down of the
385 computational domain in the numerical approach.



386

387 **Fig. 14.** Comparison of spatial correlations.

388 **6. Investigation of aerodynamic force**

389 **6.1 CFD setup**

390 A prism with the NACA 0015 airfoil section is used to investigate the relationship
 391 between the coherence of the vertical velocity fluctuations and coherence of the lift
 392 force on a slender body. The computational domain is illustrated in Fig. 15. The
 393 model is placed $45 M$ downstream of the inlet grid where the turbulence is nearly
 394 homogeneous and isotropic. **The Reynolds number at the model position is 66000 and**
 395 **the viscous effects have been considered. The span width of the model is the same as**
 396 **the width of the computational domain. The chord length of the model is $1.25 M$ and**
 397 **the incidence is 0° .** A no-slip boundary condition is imposed on the airfoil surface.

398 The mesh distribution is shown in Fig. 16. Hexahedral cells are employed in the
 399 computational domain. The mesh is equally distributed in the spanwise direction, with
 400 a length of 0.004 m. The first layer size above the airfoil surface is 0.00003 m to
 401 meet the requirement that $y^+ \leq 1$. **In the computational domain, 4.25 million cells are**
 402 **generated. The whole simulation requires 5 days of computational time.**

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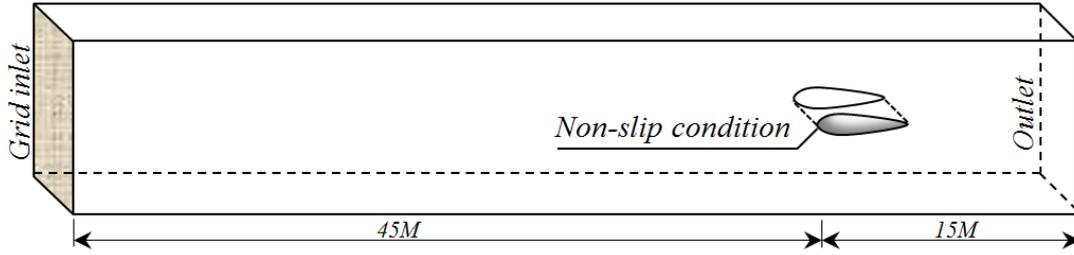
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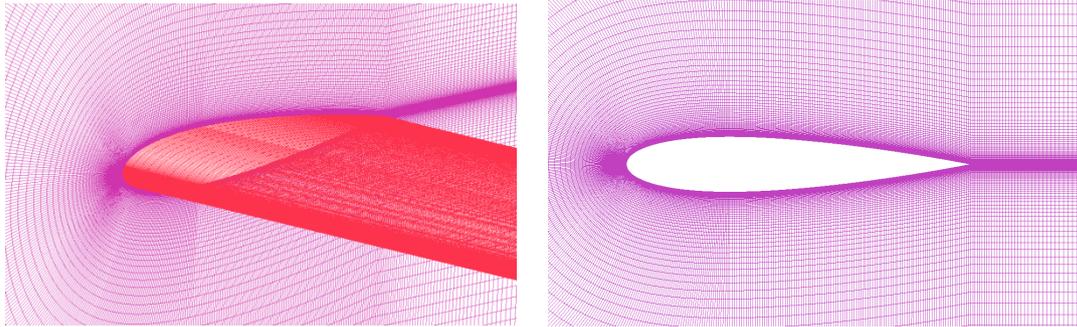
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404 **Fig. 15.** Computational domain and boundary conditions.



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406 (a)

(b)

407 **Fig. 16.** Computational mesh distribution: (a) mesh of airfoil; (b) mesh in xz plane.

408 **6.2 Results and discussion**

409 The coherence of the buffeting lift is obtained by integrating the unsteady surface
 410 pressure around several spanwise spaced strips on the airfoil model. The vertical
 411 velocity fluctuations are obtained at several observation points in the empty
 412 turbulence field at the central line of airfoil. The distribution of the strips and points is
 413 the same with Fig. 5.

414 The time histories of integrated lift on second and forth strips are shown in Fig. 17.

415 The mean values are close to zero, as the incidence of the airfoil is 0° . The spanwise
 416 correlations of buffeting lift and the vertical velocity fluctuation from the numerical
 417 simulation are shown in Fig. 18. It is clear from the figure that the buffeting lift is
 418 more strongly correlated than the vertical turbulence component. To further examine
 419 the correlation relationship between the buffeting lift and the vertical velocity
 420 fluctuation, the spanwise correlation width proposed by Larose (1997) is used:

$$421 L_w^z = \int_0^b R_{12}(\Delta y) d\Delta y \quad (8)$$

422

423

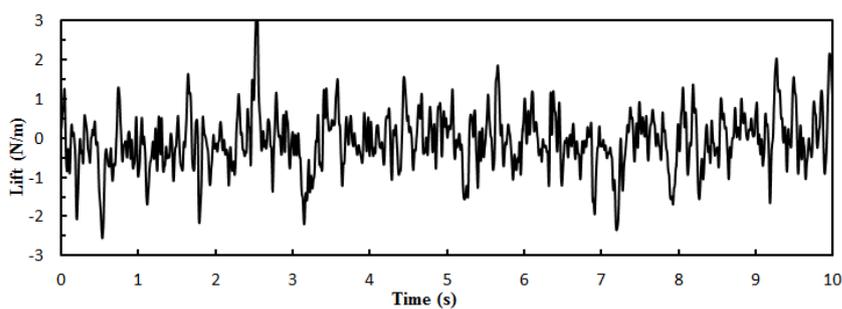
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1420 where R_{12} is the spanwise correlation function of the random variables at two points
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1422 and b is the maximum spanwise spacing. By integrating the correlation curves from
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1424 Fig. 18, the relationship is found to be $L_L^z = 3.17L_w^z$, where L_L^z and L_w^z are the
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1426 spanwise correlation widths of the buffeting lift and vertical velocity fluctuation,
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1428 respectively. The result obtained in this study is close to the results obtained by
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1430 Nettleton (Larose 1997) and Li (2015) from wind tunnel tests, which are $L_L^z = 3.6L_w^z$
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1432 and $L_L^z = 3.9L_w^z$, respectively.
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1437 This result shows that the strip assumption that uses the spatial distribution of
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1439 turbulence fluctuations to describe the spatial correlation of the buffeting lift is
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1441 incorrect. In this study, the chord length of the model is 0.05 m, which is greater than
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1443 the integral length-scale of the vertical turbulence fluctuation ($L_w = 0.023$ m). It
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1445 corresponds to the condition proposed by Nettleton (see Etkin, 1971), according to
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1447 which the strip assumption fails if the chord length of the body is close to or greater
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1449 than the integral length-scale of the vertical turbulence component.
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437 (a)

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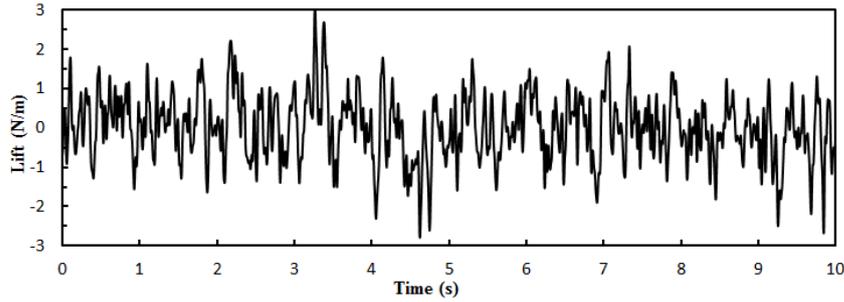
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(b)

Fig. 17. Time histories of integrated lift: (a) strip 2; (b) strip 4.

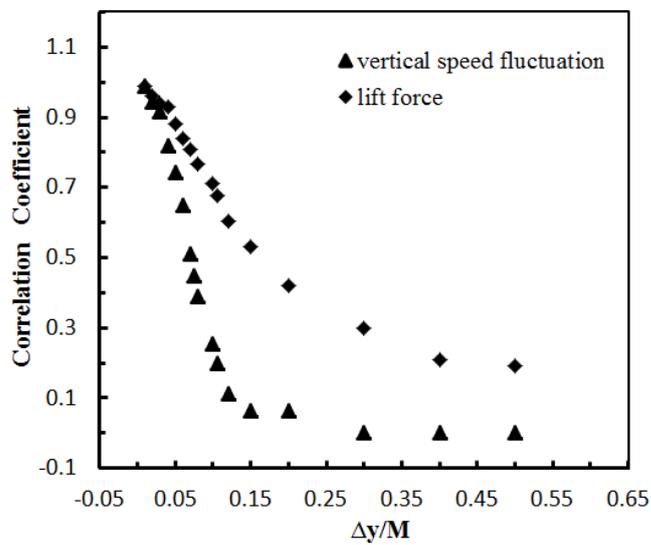
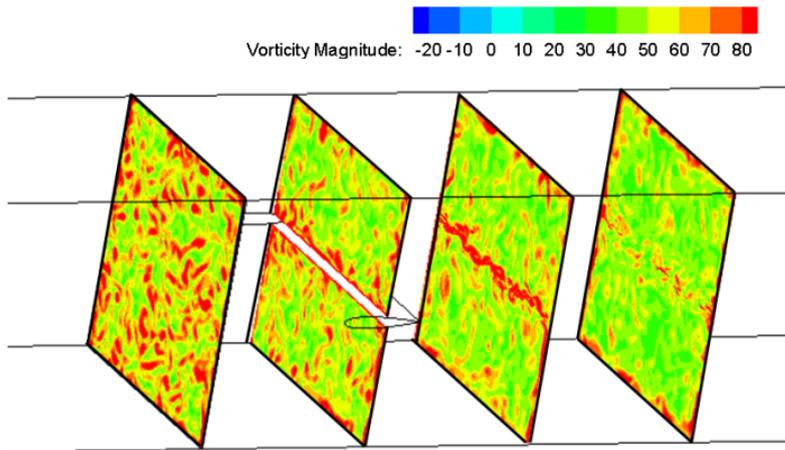


Fig. 18. Spanwise correlation relationship.

Fig. 19 shows the magnitude of the instantaneous vorticity in yz cutting planes at different airfoil positions. It is apparent that when the turbulence approaches the airfoil, the presence of the solid wall will modify the structure of the turbulence field. It can be seen from the figure that the turbulence kinetic energy produced by the variation of streamwise and vertical velocities close to the airfoil would follow a two-dimensional pattern, consequently the turbulent flow field around the airfoil may be closer to the two-dimensional (compared to the three-dimensional) background turbulence, which may yield a lift force more correlated than the velocity fluctuation.

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1538 451 Then, after passing through the airfoil, the flow structure will be three-
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1540 452 dimensionalized again by the isotropic background turbulence.
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1558 454 **Fig. 19.** Contours of instantaneous vorticity in yz planes at model positions $x = 43 M$,
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1560 455 $46 M$, $49 M$, and $52 M$.
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1563 456 To the best of the author's knowledge, this is the first time that this relationship has
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1565 457 been obtained via a numerical method. It can be concluded that the proposed method
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1567 458 for the generation of homogeneous isotropic turbulence provides high accuracy in
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1569 459 estimating the spatial distribution of the aerodynamic forces on a body immersed in a
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1571 460 turbulent flow, which is of great significance for investigations of the influence of
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1573 461 turbulence on such bodies.
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1578 462 7. Conclusion

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1581 463 A new method for generating homogeneous isotropic turbulence by modeling a grid at
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1583 464 the inlet of the computational domain has been proposed. The generated turbulence
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1585 465 field has been compared with the results of a wind tunnel test and of previous research
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1587 466 for the purpose of verification. The conclusions from this comparison can be
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1597 467 summarized as follows:
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1600 468 (1) With regard to the development of the turbulence field, the turbulence intensity
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1602 469 decay exponent is found to be $1.09 < n < 1.26$ and the length-scale growth rate is
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1605 470 found to be $0.376 < m < 0.421$.
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1608 471 (2) The spectra of the three fluctuation components fit the von Kármán spectrum. The
1609
1610 472 filter cutoff frequency is sufficiently high for the investigations in this study.
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1613 473 (3) The spatial correlations among the vertical turbulence fluctuations fit well with the
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1616 474 wind tunnel test results.
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1619 475 After the verification of the generated turbulence, a model body with NACA 0015
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1621 476 airfoil section was placed in the computational domain to determine the spatial
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1623 477 distribution of the aerodynamic lift force. The relationship between the spanwise
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1626 478 correlation width of the buffeting lift and the vertical turbulence fluctuation obtained
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1628 479 in this study is $L_L^z = 3.17L_w^z$. These results show that the strip assumption is invalid.
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1631 480 This paper has demonstrated that the proposed passive grid-generated turbulence
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1633 481 method can be used to investigate the spatial distribution of aerodynamic forces on
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1636 482 slender bodies immersed in turbulent flows. However, one drawback of this method is
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1639 483 that, in general, it incurs a high computational cost, although this may be reduced with
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1641 484 the development and improvement of computer hardware.
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1655 489 financial support to study abroad.
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