EFFECT OF TURBULENCE PARAMETERS ON FLOW-INDUCED VIBRATIONS IN A CROSS FLOW OVER STAGGERED ARRAY OF CYLINDERS

[1]JI-SU KIM, [2]JONGWOON PARK, [3]HYEON-KYEONG KIM

[1,2]Nuclear & Energy Systems Department, Dongguk University,
[3]SENTEC, South Korea
E-mail: [1]kimjs@dongguk.ac.kr, [2]parkjw@dongguk.ac.kr, [3]hkchoi@s2ntech.com

Abstract - Effect of turbulent Prandtl numbers used instandard k-ω turbulence model on the flow induced vibrationsfor cross flows over staggered array of cylinders is quantified through computational fluid dynamic analyses. For 50-60% variations in the turbulent Prandtl numbers, the difference inthe frequency ratios, the parameters for the vortex-induced vibration, are larger than 10 %. On the other hand, the difference in the reduced velocity, the parameter for fluid-elastic vibration, is3.6%.This result shows that the fluid-elastic vibration is far less sensitive to turbulence parameters.

Index Terms - Flow Induced Vibration, Cross Flow, Array of Cylinders, Computational Fluid Dynamics, Standard k-ω turbulence model, Turbulent Prandtl Number.

I. INTRODUCTION

Flow-induced vibration (FIV) in a cross flow over an array of cylinders is important in designing heat exchanger tubes, structural support columns and so on. For a group of multiple circular cylinders subjected to the cross-flow, typical vibration mechanismsarevortex-induced vibration (VIV), fluid-elastic vibration (FEV) and turbulence-induced vibration (TIV) [1].

When the natural frequency of the structure is close to the vortex-shedding frequency, the VIV occurs, which is usually interestedin a single cylinder. On the other hand, an array of multiple cylinders can oscillate with larger amplitudes due to interactions between the objects. The FEV may occur in this situation and this would be so severe that itcan cause structural failure. The TIV usually results in arrhythmic pressure drop around structures leading to vibrations [2-4]. Free vibration of circular cylinders in a tightly packed periodic square inline array of cylinders was studied by Kevlahan [5]. Pandey et al. [6] studied the flue gas flow distribution in the Low Temperature Super Heater tube bundles situated in second pass of a utility boiler and the phenomenon of flow induced vibration. Nakamura et al. [7] studied flow instability of cylinder arrays resembling U-bend tubes in nuclear steam generators. For the FIV evaluations, computational fluid dynamic (CFD) analyses after proper validations are usually used to obtain theFIV parameters such as pitch-to-diameter velocity and frequencies of drag and lift forces under turbulent flows. In the CFD, uncertainties arise from the diverse mathematical models and turbulence is one of those mostly interested.

In this paper, the effects of the turbulence model parameters such as Prandtl numbers on the VIV and the FEV are quantified for a cross flow over staggered array of cylinders.

II. METHOD OF ANALYSIS

A.CFD Analysis of Cross Flow Over Staggered Cylinders

The test conditions of the staggered cylinder array shown in Fig. 1 [8] areused in the presentanalyses.Many CFD validations [9-11] have been performedfor this test. The cylinder length is 10 cm, the mass of one cylinder is 2.588 kg and the Reynolds number is 18,000.

FLUENT CFD code[12] is used on the present purpose for solving two-dimensional (2D) unsteady Reynolds averaged Navier-Stokes (URANS) equations, where standard k-ω turbulence model is applied considering the characteristics of strong low Reynolds effect near the wall.Second order upwind numerical scheme is used.

To capture the FIV uncertainty arising from the turbulence phenomena, two Prandtl numbers for turbulent kinetic energy (TKE) (σ_k) and specific dissipation rate (SDR) (σ_ω) in the standard k-ω turbulence model are selected. The ranges of σ_k and $\sigma_\omega$reported are 0.5-1.25 and 0.5-0.856, respectively [13]. The TKE determines the energy in the turbulence and the SDR does the scale of the turbulence.

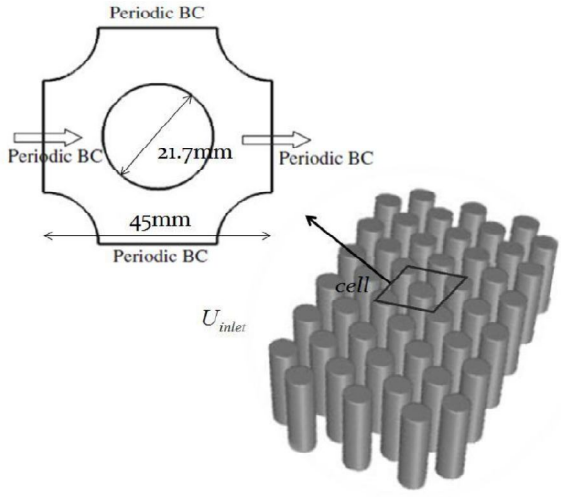


Fig. 1. Geometries of the actual and simplified staggered array of cylinders for computation [5].

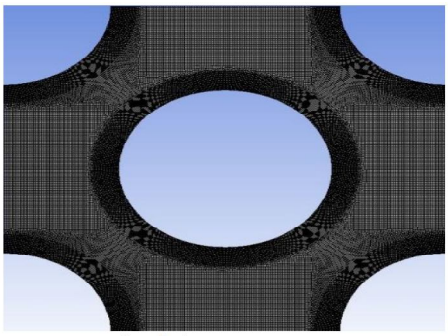


Fig. 2. Mesh of the URANS computation.

Coefficient	Case 1	Case 2
TKE Prandtl Number, σ_k	2.0	1.0
SDR Prandtl Number, σ_ω	2.0	0.8

Table 1: CFD casesfor two Turbulent Prandtl numbers

The computational domain and meshes are shown in Fig. 2. The cell size is basically 0.2 mm and the cell size near the cylinder wall is halved to 0.1 mm. Total number of the cells is 63,466. The time step size is fixed at 0.1 millisecond.

The values for the two Prandtl numbers recommended are 2.0 [12]. Two CFD cases with different combinations of the Prandtl numbers are considered for the sensitivity of the FIV as following(see Table 1):

- Case 1: Code-recommended value;
- Case 2: Lower values by 50-60% to artificially expedite the vortex shedding.

The fluid is water with the density and the viscosity are $\rho = 998.2$ kg/m^3 and $\mu = 1.003 \times 10^{-3}$ kg/m·s, respectively, at the reference temperature of 293.15 K (20 ℃). Th flow boundary conditions are all periodic for the mass flow rate of 40.75 kg/sfrom the left boundary as shown in Fig. 1.

B. Methods of FIV evaluations

In FIV, vibrations occur in two directions, transverse and parallel to the flow. In the transverse direction, the excitation force has a dominant frequency, called the Karman vortex shedding frequency. The vortex shedding is generally expressed in terms of Strouhal Number [1] as following:

$$St = \frac{f_W D}{V} \tag{1}$$

where $f_w$is the vortex shedding frequency, D is the cylinder diameter and V is the flow speed. In evaluating the structural stability under VIV, natural frequency (f_s) and vortex shedding frequency (f_w) are required for the frequency ratio, f_r, which is expressed in the following form [1]:

$$f_r = \frac{f_w}{f_s} \tag{2}$$

On the other hand, evaluating the structural stability under FEV needs reduced velocity and mass damping. The reduced velocity is calculated withpitch-to-diameter velocity, which can be expressed as following:

$$V_{pc} = \frac{VP}{P-D} \tag{3}$$

where P is the center-to-center inter cylinder pitch [15]. The reduced velocity (V_R) is a dimensionless value in the following form:

$$V_R = \frac{V_{pc}}{f_S D} \tag{4}$$

The mass damping (m_d) is given by [16]:

$$m_d = m\delta / \rho D^2 \tag{5}$$

where m is the mass per unit length, δ is the damping ratio and ρ is the fluid density.

According to the section III of the ASME Boiler and Pressure Vessel Code [17], following should be satisfied for the stable VIV:

$$0.7 \text{ (or } 0.8) \le f_r \le 1.3 \text{ (or } 1.2) \tag{6}$$

An FEV stability mapfor the mass damping in Eq. (5) and the following reduced velocity isproposed [18]:

$$\frac{V_c}{f_S D} = K\left[\frac{m\delta}{\rho D^2}\right]^{1/2} \tag{7}$$

where V_c is the critical flow velocity and K is the dimensionless factor.

III. RESULTS AND DISCUSSION

A. Cross Flow Over Staggered Cylinders

Snapshots of velocity magnitude contours for the two cases obtained from the present URANS computations are shown in Figs. 3 and 4. Park and Choi [9] validated accuracy of these computations in terms of time mean velocity profiles.

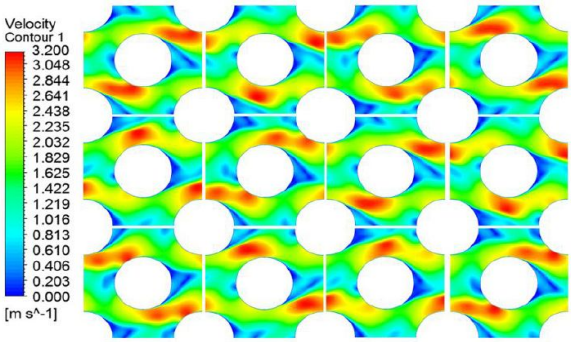


Fig. 3. Velocity magnitude contours for CFD Case 1.

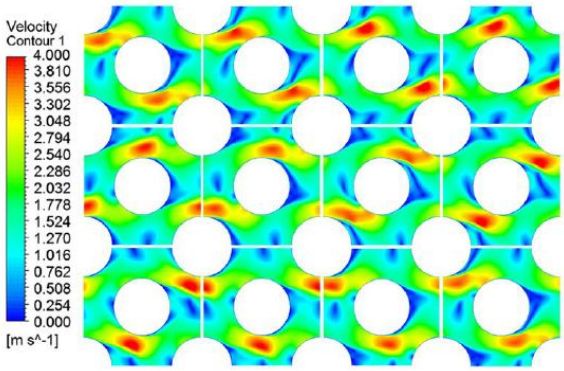


Fig. 4. Velocity magnitude contours for CFD Case 2.

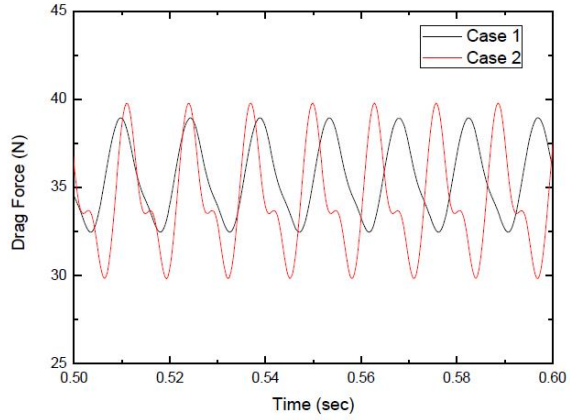


Fig. 5. Drag force variations (0.5-0.6s).

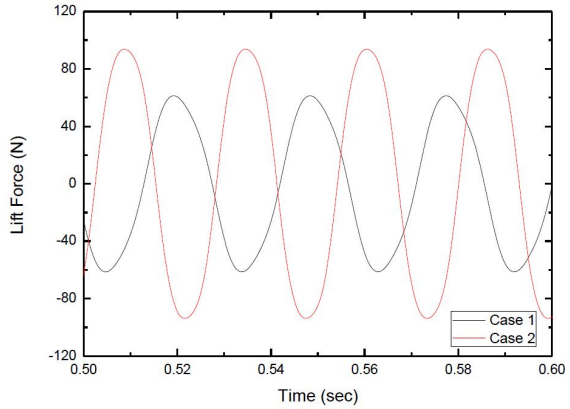


Fig. 6. Lift force variations (0.5-0.6s).

Parameter	Case 1 (Drag)	Case 1 (Lift)	Case 2 (Drag)	Case 2 (Lift)
Maximum velocity, (m/s)	3.165	3.165	4.011	4.011
In-flow mean Velocity, V (m/s)	1.777	1.777	1.830	1.830
Maximum Force, F (N)	38.97	61.36	39.76	93.76
Period, t_p(s)	0.0146	0.0219	0.0129	0.0259
Vortex Shedding Frequency, f_w (1/s)	68.73	45.64	77.52	38.61

Table 2: Computation resultsfor each CFD case

The computational results relevant to the FIV evaluations are summarized in Table 2.The mean velocities for each case obtained are 1.777 and 1.830 m/s, respectively as shown in Table 2. The velocity magnitudes range from 0 to 3.165 m/s for the Case 1 and from 0 to 4.011 m/s for the Case 2. The oscillation periods are also presented in Table 2 for the drag and the lift forces in each case. It can be found that the turbulence coefficients surely affect the flow oscillations. The larger is the velocity, the larger is the frequency (smaller periods).

The variations of drag and the lift forces between 0.5 and 0.6 s are provided in Figs. 5 and 6. Each force is obtained at the left and the bottom of the central cylinder, respectively. For the Case 1, the periods of drag and lift forces are 0.0146 and 0.0219 seconds, and the vortex shedding frequencies are 68.73 and 45.64, respectively. For the Case 2, the periods are 0.0129 and 0.0259 seconds and the vortex shedding frequencies are 77.52 and 38.61, respectively. The flow characteristics and thus the FIV parameters are somehow affected by the TKE and SDR Prandtl Numbers and these are the origin of the uncertainty in the FIV evaluations using a CFD [10].

B. Evaluations of Flow Induced Vibrations

Table 3 summarizes the VIV and FEV evaluation results. Firstly, for the VIV evaluation, Strohal number (St) is calculated from Eq.(1). The drag and the lift force Strohal numbers thus calculated for the Case 1 are 0.8394 and 0.5574, and those for the Case 2 are 0.9100 and 0.4577, respectively. The natural frequency of 18.99 Hz is referred to from an experiment for the square array [19].

The frequency ratios obtained from Eq.(2) for thedrag and lift forces are 3.62 and 2.40 for the Case 1, and 4.08 and 2.03 for the Case 2, respectively. Thus, according to the VIV stability criteria of Eq.(6),it can be decided that these two CFD cases are all stable with respect to VIV. However, the fractional differences of the frequency ratios ofthesetwo forces between the two cases are 12.7% and 15.4%, respectivelyand therefore the effect of the TKE and SDR Prandtl Numbers is not negligible for VIV.

Secondly, in the FEV evaluation, we need to calculate the mass damping from Eq.(5), which is the unique material property independentof theCFD cases. The resulting mass damping is 11.89 forgivenmass per unit length,m= 25.88 kg/m and damping ratio, $\delta = 0.0344$ [19].

Parameter	Case 1 (Drag)	Case 1 (Lift)	Case 2 (Drag)	Case 2 (Lift)
Strouhal No., St	0.8394	0.5574	0.9190	0.4577
Pitch velocity, V_{pc} (s/m)	3.432	3.432	3.535	3.535
Frequency Ratio, (f_w/f_s)	3.62	2.40	4.08	2.03
Vortex-Induced vibration (VIV)	Stable (fr > 1.3)	Stable (fr > 1.3)	Stable (fr > 1.3)	Stable (fr > 1.3)
Reduced Velocity (V_{pc}/f_sD)	8.3	8.3	8.6	8.6
Mass Damping ($m\delta/\rho D^2$)	11.89	11.89	11.89	11.89
Fluid-Elastic vibration (FEV)	Marginally stable	Marginally stable	Marginally stable	Marginally stable

Table 3: Evaluation results for VIV and FEV

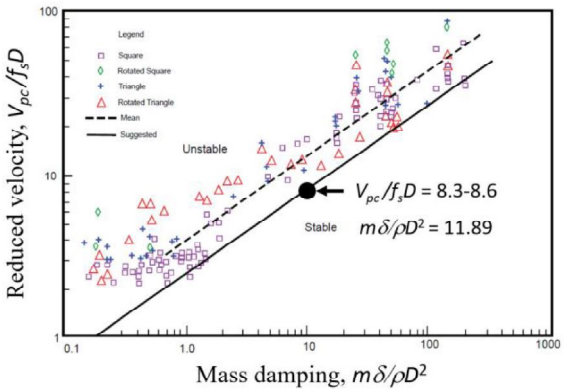


Fig. 7. FEV evaluation result.

The reduced velocities obtained by using Eq.(4) are 8.3 and 8.6 for the CFD Cases 1 and 2, respectively (these are also presented in Table 3). The fractional difference is only 3.6%. The location for these mass damping and the reduced velocity values are marked by using a solid circle in the Connors' FEV stability map [20] as shown in Fig. 7. The two casesareclose to each other and decided to be marginally stable in FEV sitting around the borderline between the stable and unstable regions. For the FEV and VIV in the cross flow over staggered array of cylinders, it is found that the effect of turbulent Prandtl numbers used in the standard k-ω turbulence model on the FEV is much smaller than on the VIV. Deciding from the literature saying that the FEV is more substantial for multiple cylinders [17], the present result can be expanded to the whole domain of the flow induced vibrations for the cross flow over staggered cylinders.

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