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Validation of a CFD code for Unsteady Flows with cyclic boundary Conditions

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1. Introduction

Currently Lilac code is under development to analyze thermo-hydraulics of a high-temperature gas-cooled reactor (GCR). Interesting thermo-hydraulic phenomena in a nuclear reactor are usually unsteady and turbulent. The analysis of the unsteady flows by using a three-dimension CFD code is time-consuming if the flow domain is very large. Hopefully, flow domains commonly encountered in the nuclear thermo-hydraulics is periodic. So it is better to use the geometrical characteristics in order to reduce the computational resources. To get the benefits from reducing the computation domains especially for the calculations of unsteady flows, the cyclic boundary conditions are implemented in the parallelized CFD code LILAC. In this study, the parallelized cyclic boundary conditions are validated by solving unsteady laminar and turbulent flows past a circular cylinder.

2. Numerical model

In this study, the incompressible Reynolds-averaged Navier-Stokes equations with the Menter's k-ω-based DES turbulence model[1] is used. All the governing equations can be cast into the following integral form:

$$\frac{\partial}{\partial t}\int \rho\phi \, dV + \int \rho\phi\vec{v}\, d\vec{S} - \int \Gamma \nabla \phi \, d\vec{S} = \int q_\phi \, dV \qquad (1)$$

Where ρ is a density of the fluid, ϕ is the dependent variable of the transport equation, $\vec{v}$ is a velocity vector, Γ is a diffusion coefficient, for example, $\Gamma = \mu$ for the momentum equation. q_ϕ is a source term of the equation.

By the context of the dual-time delta formulation, the transport equation can be written as:

$$\left[\frac{3\rho_i V}{2\Delta t} + \frac{\rho_i V_i}{\Delta \tau} + A_{\phi i}\right]\Delta\phi_i^{n+1,m} + \sum_j A_{\phi j}\Delta\phi_j^{n+1,m} = q_\phi^{n+1,m} V_i - \sum_f (C_f^{n+1,m} - D_f^{n+1,m}) S_f - \frac{\rho_i V}{2\Delta t}\left(3\phi^{n+1,m} - 4\phi^n + \phi^{n-1}\right) \qquad (2)$$

In this formulation, pseudo-time term is added to remedy the errors from the linearization of the equation, which is similar to a term in the iterative under-relaxation formulation. A second order backward differencing is used for the physical time derivative (Δt), and the Euler implicit differencing is employed for the pseudo-time derivative ($\Delta\tau$). In this study, second-order upwind or central differencing scheme is used for the convective flux and second-order central scheme is used for the diffusive flux on the right hand side, which determines finally the accuracy of the solution when it is converged to the steady state.

Generally, the pressure gradient term included in the momentum equation is not known priory. With the approximate solution of a pressure filed, the velocity calculated from the momentum equation is not correct. So it is necessary to correct the velocity in order for the mass conservation. The equation for the mass correction is derived by using the SIMPLEC algorithm.

3. Numerical Results

Flow past a circular cylinder has been studied experimentally and numerically for a long time because it has many interesting flow phenomena dependent on the Reynolds number of the cylinder. It was found that the wake flow undergoes three-dimensional transitional instabilities beyond Re~180. So a three-dimensional numerical method must be used to resolve the flow structure when the Reynolds number is larger than 180.

Here in order to evaluate the accuracy of the LILAC code, the unsteady flow around the circular cylinder is studied at Re = 300. As mentioned above, the flow undergoes three-dimensional instability. So the solution is dependent on the span-wise length of the cylinder. To overcome the problem, cyclic boundary conditions on the two end planes of the span-wise direction can be used. In this study, the cyclic boundary condition is used with the span-wise length equal to πD as recommended in ref. [2], which is enough to capture span-wise flow structure. Fig. 1 shows the flow domain and the grid used for the flow analysis whose cell size is 1,564,800.

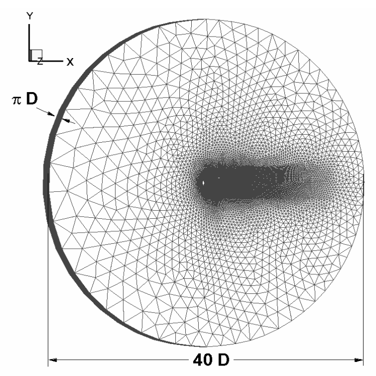

Fig. 1 Solution domain and mesh for a 3-D cylinder flow

In usual 2-D simulations, it is found that the evolutions of the drag and lift coefficients are stably periodic. But as shown in fig. 2, the coefficients are unstably periodic with the 3-D simulation.

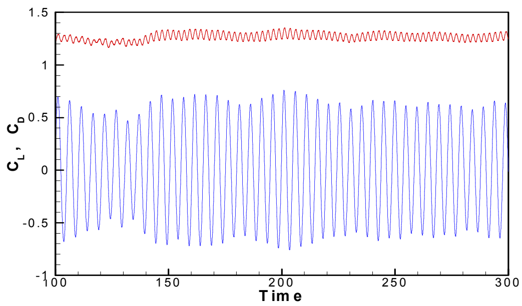

Fig. 2 Time-histories of the drag and lift coefficients for the circular cylinder at Re=300

The main reason of the amplitude fluctuation of the drag coefficient is from the three-dimensional flow structure generated in the span-wise direction as shown in fig. 3 which depicts the iso-vorticity surface at $\omega_x = 0.15$. Fig. 4 is cross-sectional views of streamwise vortex structures. The von Karman vortex streets behind the cylinder are clearly shown in the figure. Fig. 4(a) is the experimental visualization by using aluminum flakes[2], and fig. 4(b) is a result from a DNS computation by Noack[2]. The current result shown in fig. 4(c) is very similar to the other ones.

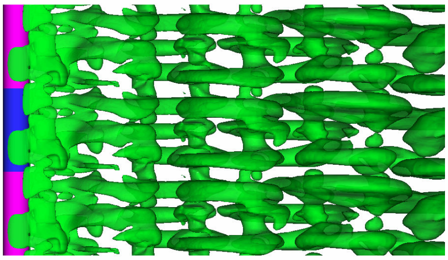
Fig. 3 Iso-surface of x-vorticity, $\omega_x = 0.15$

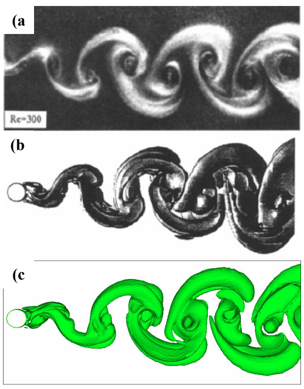

Fig. 4 Vortical flow behind the cylinder, (a) experimental visualization by using aluminum flakes (Williamson), (b) DNS result by Noack, (c) current numerical result

Breuer[3] studied turbulent flow past a circular cylinder at Re=3,900 with a larger eddy simulation. At the Reynolds number equal to 3,900 which is sub-critical, the flow separates on the cylinder surface laminarly before undergoing a transition to turbulent boundary layer. In this study, the turbulent flow past the circular cylinder at Re=3,900 is numerically simulated by using the LILAC code with the DES model.

From the fig. 5, it is observed that the drag and lift coefficients are varying very unstably. The averaged C_d from the current results with the DES method is 1.03 which is very similar to the experimental data[4], which are depicted in table 1. The distribution of the time-averaged pressure coefficients on the cylinder surface is plotted and compared with the experimental data. It is thought from the figure that it is predicted very well.

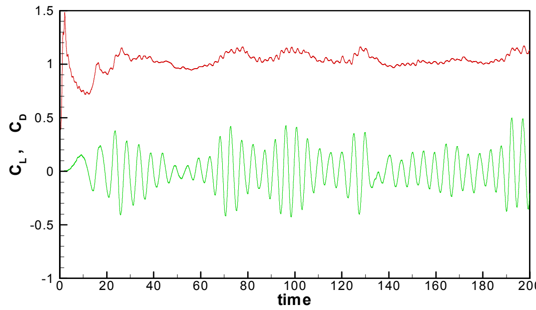

Fig. 5 Time-histories of the drag and lift coefficients for the circular cylinder at Re=3,900

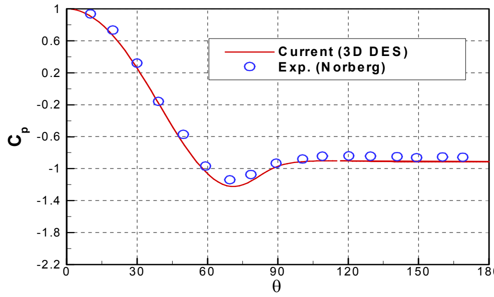

Fig. 6 Time-histories of the drag and lift coefficients for the circular cylinder at Re=3,900

Table 1 Comparisons of the computed parameters with the experimental results.

	Strouhal number	Cd
Exp. (Norberg)	0.215±0.005	0.98±0.005
Calculated (DES)	0.212	1.03

4. Conclusion

To get the benefits from reducing the computation domains especially for the calculations of unsteady flows, the cyclic boundary conditions are implemented in the parallelized CFD code LILAC, and validated by solving unsteady laminar and turbulent flows past a circular cylinder. From the study, it can be concluded that the three-dimensional flow structures are well resolved with the method.

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