Research Article

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High order accurate numerical simulation of flow past an oscillating circular cylinder

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Introduction

Over the years, flow past circular cylinder has been studied[1–11] extensively due to its academic and practical significance. Periodic lift and drag forces are generated over the cylinder due to separation and vortex shedding leading to structural vibration also known as vortex induced vibrations (VIV). This fluid-structure interaction (FSI) may result in serious engineering problems such as fatigue failure of the off-shore riser and sub-sea pipelines. Therefore, prediction of fluid forces on the cylinder has great importance from the point of view of structural design. Often, two types of FSI problems involving cylinder are studied. In one case, cylinder oscillates due to the in-line and transverse forces generated by vortex shedding.[1–10] In the second case, the cylinder is forced to oscillate in a transverse direction with prescribed oscillating amplitude and excitation frequency, known as force induced vibration (FIV).[11] In this paper, the FSI problems are studied using a numerical method. An accurate Harten Lax and van Leer with contact for artificial compressibility (HLLC-AC) Riemann solver[12–14] developed for solving incompressible flows in artificial compressibility formulation have been used for flow computation. The Riemann solver is modified to incorporate Arbitrarily Lagrangian-Eulerian (ALE)[15] formulation in order to take care of mesh movement in the computation, where radial basis function[16] is used for dynamically moving the mesh. Higher order accuracy is achieved using quadratic solution reconstruction based on solution dependent weighted least squares (SDWLS).[17] The results obtained by the present method is validated those reported in the literature.[1–11]

Arbitrarily Lagrangian-Eulerian (ALE)[15] formulation

An artificial compressibility[18] based, with dual-time stepping, the unsteady Navier-Stokes incompressible equations is modified here to take care of moving boundaries using the Arbitrarily Lagrangian-Eulerian (ALE)[15] formulation. The integral form of the two-dimensional governing equation in arbitrarily Lagrangian-Eulerian form can be written as

$$\iint_{\Omega}\frac{\partial W}{\partial\tau}dxdy + I^M\iint_{\Omega}\frac{\partial W}{\partial t}dxdy + \Theta^M\oint_A\left[\left(E^c+E^v\right)n_x+\left(F^c+F^v\right)n_y\right]dA = \iint_{\Omega}S_0dxdy \quad (1)$$

$$W=\begin{Bmatrix} p/\rho \\ u \\ v\end{Bmatrix};E^c=\begin{Bmatrix} U \\ Uu+p/\rho \\ Uv\end{Bmatrix};G^c=\begin{Bmatrix} V \\ uV \\ vV+p/\rho\end{Bmatrix};$$

$$E^v=\begin{Bmatrix} 0 \\ \sigma_{xx} \\ \sigma_{xy}\end{Bmatrix};G^v=\begin{Bmatrix} 0 \\ \sigma_{yx} \\ \sigma_{yy}\end{Bmatrix} \quad (2)$$

$$I^M=\begin{Bmatrix} 1&0&0 \\ 0&1&0 \\ 0&0&1\end{Bmatrix};\quad \Theta^M=\begin{Bmatrix} \beta^2&0&0 \\ 0&1&0 \\ 0&0&1\end{Bmatrix};S_0=\begin{Bmatrix} 0 \\ f_{e,x} \\ f_{e,y}\end{Bmatrix} \quad (3)$$

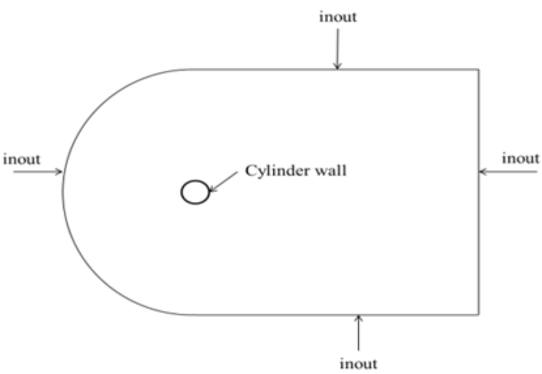
Where $U=u-x_t$ and $V=v-y_t$ are the convective velocities in referential frame with x_t and y_t are the velocities of the moving grid in X and Y directions respectively. Note that, equation (1) does not exhibit any physical meaning until pseudo time steady state, i.e. $\left(\frac{\partial p}{\partial\tau}=\frac{\partial u}{\partial\tau}=\frac{\partial v}{\partial\tau}\cong 0\right)$ is reached. As the pseudo-steady state is reached, the equations are identical to the original unsteady incompressible Navier-Stokes equations in ALE form. Now splitting the convective fluxes $(E^c andG^c)$ of equation (1) into stationary reference flux and ale flux part as,

$$\iint_{\Omega}\frac{\partial W}{\partial\hat{o}}dxdy + I^M\iint_{\Omega}\frac{\partial W}{\partial t}dxdy + \Theta^M\oint_A\left[\left(E^c_{St}+E^v\right)n_x+\left(F^c_{st}+F^v\right)n_y\right]dA - \oint_A\left[\left(E^c_{ale}\right)n_x+\left(F^c_{ale}\right)n_y\right]dA = \iint_{\Omega}S_0dxdy \quad (4)$$

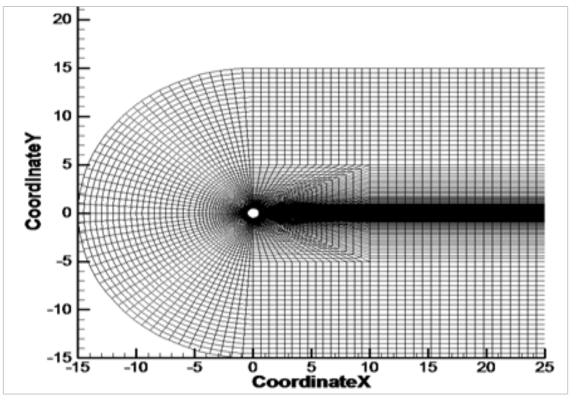
Now equation (4) can be discretized in a very similar manner to that for unsteady Navier-Stokes equation for stationary boundary problem.[12–14] The additional effort need to be added for ale flux vector. This additional term, ale flux, is nothing but the volumetric increment along the face and can be evaluated by considering the Geometric Conservations Law (GCL).[19] The radial basis function:[16] Thin-Plate Spline (TPS) with global support is used for mesh movement. The Thin Plate Spline with global support generates meshes of high quality after deformation along with the computational efficiency. The fluxes at cell interface, that is, the stationary reference convective fluxes are evaluated using the Harten Lax and van Leer with contact for artificial compressibility (HLLC-AC)[12–14]Riemann solver where interface values are reconstructed based on solution dependent weighted least squares (SDWLS).[17] In the present case, Higher order accuracy is achieved using quadratic solution reconstruction. For viscous fluxes, a central differencing method based on Green-Gauss approach is used.

Results and discussion

In the present paper, following two different cases for an oscillating circular cylinder is simulated. Figure 1 shows the domain considered as well as boundary conditions applied. Based on the mesh convergence study, a quad grid having 13840 mesh element and 13620 nodes is selected for the simulation. Case (1) Vortex-induced vibration (VIV) at Reynolds number (Re) 150: Here, an equation of motion is used to represent VIV of a cylinder oscillating in the transverse direction (normal to the flow) as: $m\ddot{y} + c\dot{y} + ky = F$ where, m = structural mass, c = structural damping coefficient, k = spring constant, and F = fluid force acting in the transverse direction (lift force). Figure 2 shows the comparison of the results obtained with the literature[7,8,10] against the displacement amplitude of the cylinder which is free to vibrate in the transverse direction for various reduced velocities $\left(U_r = \frac{U}{Df_n}\right)$ at Re =150. From Figure 2, it can be seen that the simulation results produced using present formulation agree well with the literature data.[7,8,10] The maximum transverse amplitude occurs at a reduced velocity $U_r = 4$. with Y_{max}= 0.5316. Hence we can infer that the lock-in region for Re=150, m=8/π lies at $U_r = 4$. Case (2) Forced induced vibrations (FIV) at Reynolds number (Re) 100: simulation of the forcefully oscillating cylinder having diameter D=1 is performed here. The transverse motion, $y(t)$ is given by the harmonic oscillation equation: $y(t) = A\sin(2\pi f_0 t)$ where, maximum amplitude, $A = 0.25$ with oscillation frequency, $f_0 = 0.084$ is used, which is similar to that of literature.[11] Figure 3 shows the comparison of the results obtained with the literature data[11] against the Lift co-efficient and time. It can be seen that the results agree well with the results of Placzek et al.[11]



A Domain used



B Mesh used

Figure 1 Domain and mesh used for an Oscillating circular cylinder problem.

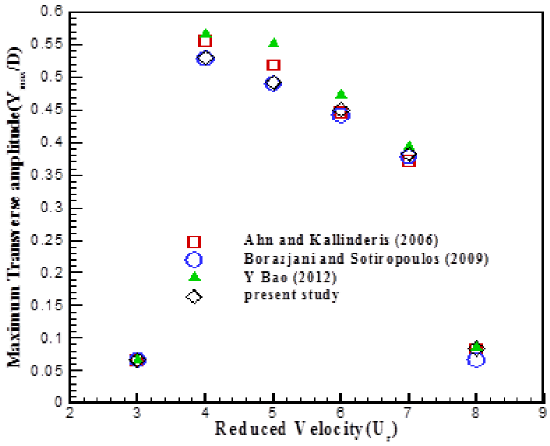


Figure 2 Comparison of maximum Transverse.

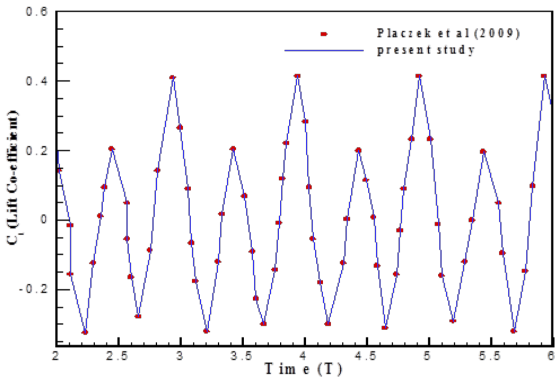


Figure 3 Time series of the fluctuating lift amplitude of single circular cylinder undergoing coefficient at f_0=0.084VIV with m=8/π at Re=150.

Conclusions and contribution

An accurate Harten Lax and van Leer with contact for artificial compressibility (HLLC-AC) Riemann solver with Arbitrarily Lagrangian-Eulerian (ALE)[15] formulation has been developed and used for computing flow past an oscillating cylinder. The results obtained by the present solver matches well with that reported in the literature.

Acknowledgments

None.

Conflicts of interest

The authors declare that there is no conflicts of interest.

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