The Numerical Simulation of Fluid-Structure Interaction on a Simple Cluster in an Axial Flow

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When the coolant flows through fuel assemblies in pressurized water reactor (PWR) core, the rods, which constitute the assembly, are induced to vibrate by the coolant. This vibration is called axial-flow-induced vibration and is important for the PWR safety. The amplitude of this vibration is very small, however, it would fret and wear the rods so that the radioactive material may be released [1]. On the other hand, there may exist the instability [1], after which the vibration of the rod could be enhanced dramatically. Therefore, it is crucial for the PWR safety to understand the vibration of the rod.

The axial-flow-induced vibration is essentially a fluid-structure interaction (FSI) problem and has been studied theoretically by many researchers by simplifying the FSI. The rod can be considered as a cylinder, modeled by Euler-Bernoulli beam. One important parameter influencing the dynamics of the system is the dimensionless flow velocity [1], which is defined with the mean flow velocity, the Young's modulus of the cylinder and other flow and structure parameters. For the small dimensionless flow velocity, there is no instability, however, the instabilities including buckling and flutter insanities instabilities could occur if the dimensionless flow velocity is large enough [1]. This is also observed by experiments [1].

The theoretical analyses do not take into account FSI completely, e.g. the forces imposed on the cylinders (rods) by the flow are not calculated based on Navier-Stokes (N-S) equations. Therefore, the theoretical analyses may not predict the dynamics accurately. The linear theories can not predict the vibration after the instability and the nonlinear theories [2] can do for a single cylinder system, however, it is very difficult to build a nonlinear theory for a cluster consisting of several cylinders in an axial flow. On the other hand, the experiments could not obtain much detailed dynamic information. Thus, to understand the dynamics more detailed, we try to simulate FSI numerically for a simple cluster consisting of four cylinders in an axial flow.

The model is shown in Fig. 1. All cylinders, modeled by Euler-Bernoulli beams, have D diameter and $20D$ length and are clamped in an axial turbulent flow, which is confined by a cylindrical wall, having the same length as the cylinders and $6.8284D$ diameter. All cylinders are hollow with $0.06D$ thickness. The global coordinates system is right hand and the flow direction is z direction. For each cylinder, we define two local directions R and T. The flow velocity at the inlet is a constant υ_0 and the pressure at the outlet is zero. The FSI is solved numerically by the partitioned scheme [3], which is shown in Fig. 2. The flow solver is the commercial CFD software Fluent 12.0 [4] and the structure is the in-house Euler-Bernoulli beam solver, which is integrated into Fluent by the user-defined functions (UDFs) provided by Fluent. Within one time step, the mesh in the fluid domain is updated by

Fluent with the spring analogy method. The turbulence model is large eddy simulation (LES) model and the sub-grid scale (SGS) model is Smagorinsky-Lilly model with Smagorinsky constant C_S being 0.1 [4].

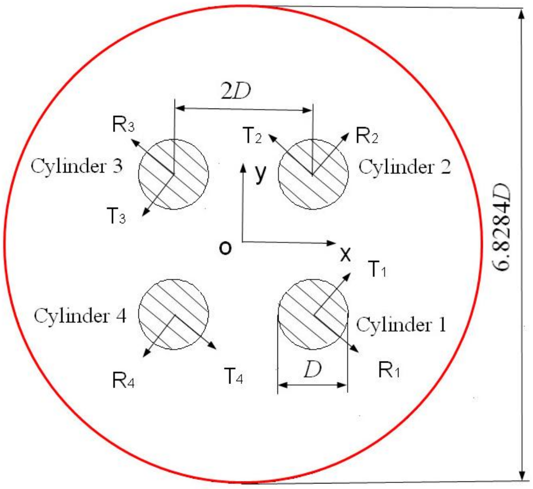

Figure 1 the model

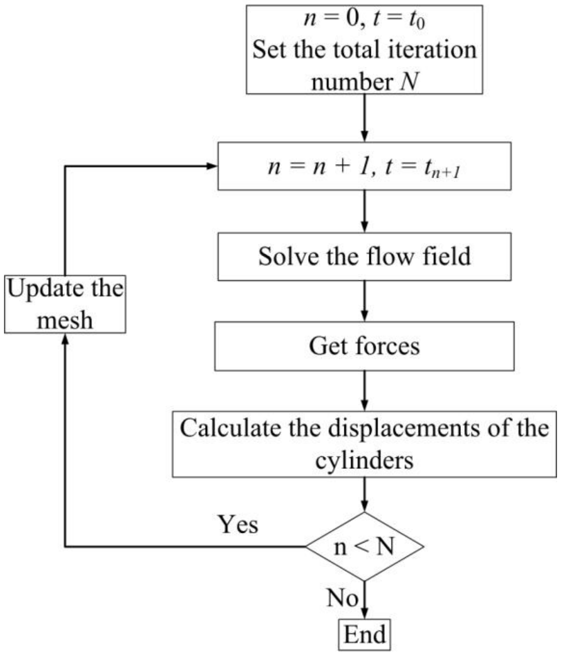

Figure 2 the FSI coupling scheme

The simulations for two different dimensionless flow velocities 4.4499 and 6.0173 were conducted. In the first case, cylinder #1 is initially located as the first beam shape with the maximum displacement $0.2D$ in its R direction but in equilibrium state in its T direction. It is found that this initial vibration is damped into a weak oscillation, which can be attributed into turbulence. In the second case, all cylinders have no initial displacements in all directions. However, all cylinders are buckled finally with the maximum displacement about $0.16D$, which indicates a buckling instability. A weak oscillation is also induced by turbulence for each cylinder. For each cylinder, the buckling displacement in R direction is larger than that in T direction, and the bucking shapes in R and T directions are dominated by the first beam mode shape.

References

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