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Two-dimensional simulation of laminar flow around four two-degree-of-freedom cylindrical cylinders in a rectangular arrangement using random vortex-boundary element method

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Abstract

Flow-induced vibration is a significant factor in the mechanical destruction of structures exposed to fluid flow. This study uses random vortex-boundary element methods to simulate two-dimensional laminar fluid flow around four cylindrical cylinders with one and two degrees of freedom, arranged in a rectangle. Hydrodynamic force coefficients, streamlines, and cylinder displacements were plotted. The vorticity distribution was separated into blob-vortexes, and their changes were studied by tracking in the Lagrangian approach, considering two mechanisms of convection and diffusion in each time step. Vortex sheets were created on the boundary, satisfying no-slip boundary condition. The cylinder vibrations were modeled as a mass, spring, and damper system. Results showed that for 1 and 2DoF, the average drag coefficient changes were 0.84 and 0.97, respectively, compared to the stationary cylinder. The rear cylinders had less vibration amplitude than the front cylinders. The y-amplitude was three times larger than the x-amplitude. The maximum x-amplitude vibration of 1DoF cylinders was 1.51 times larger than 2DoF ones. Solving flow over 2DoF single cylinder using BEM, with a similar solution in Ansys-Fluent software, showed a 25% reduction in runtime and a 2.3% increase in calculation accuracy, without the need for homodis mapping or considering the vortex images.

Keywords: flow-induced vibration; Random vortex; boundary element; four cylindrical cylinders; laminar flow.

1. Introduction

Flow-induced vibrations (FIV) are a significant factor in reducing the lifespan and structural integrity of a variety of engineering structures exposed to fluid flow, such as offshore platforms, chimneys, power lines, airfoils, and heat exchangers. This issue is particularly acute in the nuclear industry's heat exchangers but also affects other industrial heat exchangers where high-velocity flows can lead to vibration. One specific challenge is the asymmetric vortex shedding at certain Reynolds numbers, causing periodic hydrodynamic forces that can resonate with a structure's natural frequency, leading to amplified 'lock-in' vibrations. [1]

FIV research has been active since the 1960s, focusing on a multitude of factors, from the degrees of freedom (DoF) of the objects to the flow regime and Reynolds numbers. Studies involve experimental and numerical methods to investigate flow characteristics, heat transfer rates, dimensionless number calculations, energy extraction, and methods for vibration control. Significant research contributions include categorizing flow regimes by Reynolds numbers, simulating boundary layer flows, and developing advanced methods to solve for transient diffusion, as well as techniques to simplify complex geometries within computational models. The combined random vortex-boundary element method possesses essential capabilities for accurately calculating hydrodynamic forces, reducing computational errors, shortening solution times, and accommodating complex geometries without the need for vortex image applications, homogeneous mapping, or auxiliary models for turbulent flow simulations. [2]

This study represents the first attempt to employ a combined method for simulating FIV around four 1 and 2DoF cylinders in rectangle arrangement, supported by the development of a Fortran-based numerical code. The analysis of force coefficients, trend of displacement and flow patterns provides valuable insights into how the configuration of the cylinders and Reynolds number influence hydrodynamic forces, displacement and their temporal variations. These findings are crucial for industrial design and understanding the behavior of structures subjected to fluid flow. The novelties of this study include:

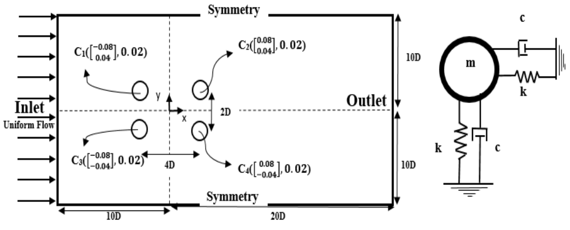
1. Simulation of FIV around stationary 1 and 2DoF circular cylinders in rectangle arrangement using Combined RVM-BEM.
2. Investigation and comparison trend of 1 and 2DoF cylinders displacement and hydrodynamic coefficients.

2. Methodology

The article details a combined RVM-BEM to simulate fluid flow around structures by solving unsteady Navier-Stokes equations in a transient flow regime, the solution is based on the Poisson equation ($\boldsymbol{\Delta\psi} = -\boldsymbol{\omega}$) and the vorticity transport equation ($\frac{\partial \boldsymbol{\omega}}{\partial \boldsymbol{t}} + \boldsymbol{u} \cdot \boldsymbol{\nabla\omega} = \frac{\mathbf{1}}{\mathbf{Re}} \Delta\omega$). The vorticity field is discretized in two distinct regions: vortex blobs for the main flow and vortex sheets near structural boundaries. To compute forces on the structures, it employs numerical methods and considers the structures as systems with mass, spring, and damper elements. The method iterates over these calculations at each time step, accurately capturing the interaction between the fluid and the structures.[3]

3. Discussion and Results

This study uses random vortex-boundary element methods to simulate two-dimensional laminar fluid flow around four 1 and 2DoF cylindrical cylinders with arranged in a rectangle at Reynolds number of 200. Hydrodynamic force coefficients, streamlines, and.



Computational Domain **2DoF cylinder**

Figure1. Schematic diagram of computational domain for 4 cylinders in a 4:2 aspect ratio rectangle arrangement

In industrial design, particularly in heat exchangers, the displacement of cylinders due to fluid interaction is a critical factor. Collisions or damage to cylinders from surpassing their elastic thresholds can occur. Research illustrated in Figure 3 suggests that 1DoF cylinders show more significant transverse displacement in comparison to 2DoF cylinders, as further detailed in Figure 2. The study finds that front cylinders experience higher vibrational ranges perpendicular to the flow direction than rear ones due to the initial impact of the fluid, which is mitigated for the rear cylinders by the front acting as a shield. Despite varying displacements, all cylinders share the same vibrational frequency. Additionally, the research observes noticeable out-of-phase vibrations in the transverse direction for both sets of cylinders positioned vertically, indicative of a repulsive inter-cylinder force. The data reveals that the peak amplitude of vibration for front cylinders is approximately 0.56 times the cylinder diameter, whereas, for the rear cylinders, this maximum displacement decreases by 25% to 0.42, highlighting the protective effect of cylinder positioning on vibrational impact.

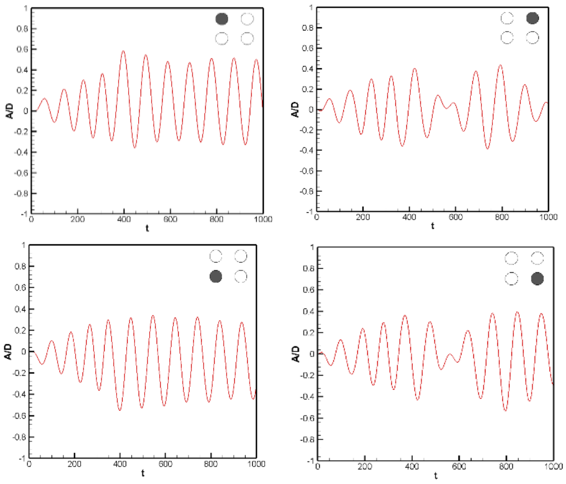


Figure 2. Vertical displacement of 1DoF cylinders at Re=200

Figure 3 present displacement and lift and drag coefficients of 2DOF cylinders at Reynolds number of 200.The cylinders displayed significant initial displacements, about 0.40 times their diameter, in the flow direction. As they settle into equilibrium, the front cylinders stabilize at a point 0.23 times their diameter from their initial position, and the rear cylinders at 0.08 times, oscillating around these new centers. Notably, for the front cylinders, the peak oscillation amplitude perpendicular to the flow is almost three times greater than that in the flow direction, with a transverse-to-diameter ratio of 0.37 compared to a longitudinal ratio of 0.12. The rear cylinders show a similar proportional relationship between the displacement directions, but with overall smaller amplitude ranges, supporting their position behind the front cylinders which are subject to more significant fluid forces, as also indicated by their larger force coefficients. The study further observes that the front cylinders follow an elliptical motion path, whereas the downstream cylinders exhibit a more complex, figure-8 pattern, consistent with the motion observed for a single 2DoF cylinder at a Reynolds number of 200. As a key result, the transverse oscillation amplitude of 1DoF cylinders was found to be 1.51 times greater than that of their 2DoF counterparts.

An examination of lift and drag coefficients highlights their significant impact on the vibrational characteristics of cylinders within a fluid flow.

Notably, front-facing cylinders exhibit elevated lift and drag coefficients in comparison to their rear counterparts. The latter encounter diminished and sporadic oscillations due to their positioning within the vortex wakes generated by the cylinders at the forefront. This positioning prompts irregularities in the oscillatory behavior of the rear cylinders, influenced by varying pressures that arise as vortices intermingle with the fluid flow. The presented data reveal an initial sharp decrease in the drag coefficient, a measure taken to ensure computational stability, which indicates a transient phase amidst fundamentally steady-state flow conditions at the specified Reynolds number. This flow behind the cylinders is asymmetrical owing to the periodic formation of vortices, resulting in a non-uniform lift force and, consequently, cyclic variances in the lift coefficient. Further analysis confirms that cylinders with degrees of freedom are subjected to greater drag forces compared to their stationary counterparts, highlighting a dynamic interplay between structure flexibility and fluid dynamics.

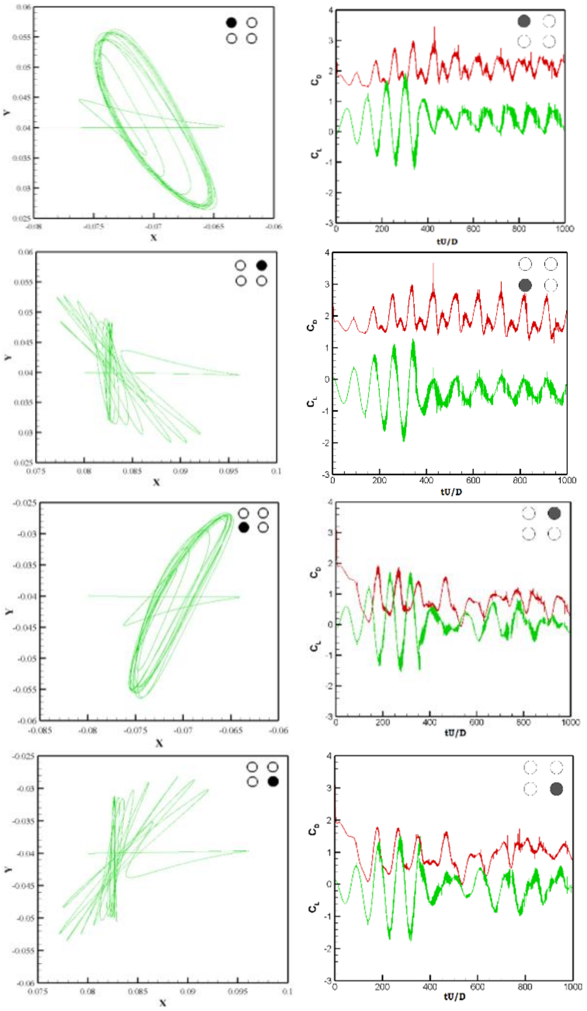


Figure 3. Displacement, Lift and drag coefficients 2DoF cylinders at Re=200

4. Conclusions

In heat exchanger design, cylinder movement from fluid forces is crucial. Exceeding elastic limits can cause damage. Studies show that:

- 1DoF cylinders exhibit greater transverse displacement than 2DoF cylinders.
- Front cylinders vibrate more than rear ones, which are shielded and show 25% less displacement.
- All cylinders share the same vibration frequency but different phases.
- Front cylinders displace more (0.56 times diameter) than rear (0.42 times).
- Front and rear cylinders have elliptical and figure-8 motion patterns, respectively.
- 1DoF cylinders' transverse vibration is 1.51 times that of 2DoF cylinders.
- Vibrational characteristics are influenced by varying lift and drag coefficients.
- Degrees of freedom in cylinders affect drag forces, linking structure flexibility to fluid dynamics.

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