Flow-Induced Vibration of Wire-Wrapped Rods in High-Speed Gas Environments

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Abstract

As research and development of high-temperature gas-cooled reactors continue to advance, the flow-induced vibration issue of wire-wrapped rod structures under high-temperature, high-velocity gas flow has attracted widespread attention. Compared with water or liquid metal coolants, gaseous working fluids exhibit higher flow velocities, lower densities, and more intense turbulence, rendering flow-induced vibration simulation analysis considerably more challenging. Based on structural vibration equations and large eddy simulation, a refined fluid-structure interaction analysis model for a single wire-wrapped rod was developed using Star-CCM+ and Abaqus co-simulation technology, accounting for nonlinear boundary effects such as gaps and friction. Wind tunnel experiments were conducted to validate fluctuating pressure and structural displacement; at an inlet flow velocity of 60 m/s, both numerical simulation and experimental results for the root-mean-square displacement of the single wire-wrapped rod were approximately 60 m. This study establishes a validated computational methodology for flow-induced vibration response of wire-wrapped rods in high-speed gas environments, applicable to the analysis and assessment of flow-induced vibration in wire-wrapped rod structures within high-temperature gas-cooled reactors.

Full Text

Study on Flow-Induced Vibration of a Wire-Wrapped Rod in a High-Speed Gas Environment

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Abstract

With the ongoing development of high-temperature gas-cooled reactors, flow-induced vibration in wire-wrapped rod structures under high-temperature, high-speed gas flow has garnered widespread attention. Compared to water or liquid metal coolants, gaseous working fluids exhibit higher flow velocities, lower densities, and more severe turbulence, making the simulation and analysis of flow-induced vibration significantly more challenging. Based on structural vibration equations and large eddy simulation (LES), this study employs a co-simulation technique using Star-CCM+ and Abaqus, incorporating nonlinear factors such as boundary gaps and friction to establish a refined fluid-structure interaction (FSI) model for a single wire-wrapped rod. Wind tunnel experiments were conducted to validate the fluctuating pressure and structural displacement. Under an inlet wind speed of 60 m/s, both numerical simulations and experimental results yielded root mean square (RMS) displacement values of approximately 60 m for the single wire-wrapped rod. This research establishes a validated computational methodology for analyzing flow-induced vibration responses of wire-wrapped rods in high-speed gas environments, which can be applied to the analysis and evaluation of flow-induced vibration in wire-wrapped rod structures within high-temperature gas-cooled reactors.

Keywords: high-speed gas; wire-wrapped rod; flow-induced vibration; fluid-structure interaction; contact boundary

Introduction

High-temperature gas-cooled reactors have become a focus of next-generation nuclear energy technology development worldwide due to their excellent economic performance and site applicability. However, flow-induced vibration in wire-wrapped rod bundle structures induced by high-speed gas can lead to fretting wear of fuel assemblies and even nuclear leakage, affecting the safe and stable operation of reactors. Currently, while the engineering community has shown considerable interest in experimental and simulation methods for flow-induced vibration of wire-wrapped rod bundles, research has primarily concentrated on water or liquid metal coolants, with limited studies on flow-induced vibration caused by high-speed gas. Compared to heavy fluids such as water or liquid metal, gaseous working media feature higher flow velocities, lower densities, and more severe turbulence phenomena, making the simulation of flow-induced vibration more challenging and necessitating dedicated research on analytical methods and experimental validation.

The wire-wrapped fuel rod consists of a cylindrical tube body axially fixed at both ends by end plugs, with a helically wound wire providing radial positioning. In lead-bismuth and sodium-cooled fast reactors, Brockmeyer et al. [**?**, **?**]

established a seven-rod model with wire wraps and a one-way coupling computational method for solving flow-induced vibration, analyzing the influence of wire wraps on system modal characteristics. Dolfen et al. [?] employed a fluid force spectrum conversion method for long-duration forces, approximating the gap between wire-wrapped fuel rods as rigid baffles. De Santis [?] investigated one-way FSI problems for wire-wrapped cylinders in axial flow using Star-CCM+ with the SST turbulence model, presenting the wire wrap' s influence on the flow field and calculating structural dynamic deformation. However, due to model complexity, transient two-way FSI calculations were not feasible. These studies adopted simplified treatments such as rigid baffles or degree-of-freedom constraints for contacts between wire-wrapped rods and between rods and end caps.

For flow-induced vibration of wire-wrapped rods in water, Wu Licun [?] and Liu Yu [?] established simplified analysis models and investigated the flow-induced vibration mechanism under leakage flow based on random vibration theory. Chen Deqi and Liu Haidong [?] solved fluid-structure coupling problems using dynamic mesh technology based on Euler-Bernoulli beam theory. Huang Heng [?] and Qi Huanhuan [?] developed amplitude expressions for fuel rods under turbulent excitation in both axial and transverse directions based on random vibration theory.

In two-phase flow or gas environments, Dae et al. [?] conducted experimental studies on flow-induced vibration of wire-wrapped rod bundles in air-water two-phase flow, investigating correlations between flow velocity, wire pitch, thickness, and vibration. Wang et al. [?] performed experimental studies on flow-induced vibration characteristics of a single wire-wrapped rod in air, measuring vibration responses under different constraint modes and inlet velocities of 1-3 m/s using a laser Doppler vibrometer (LDV). Results showed that the displacement amplitude under fixed-fixed constraints was 84% lower than under simply-supported conditions, and that wire wrap structures significantly disturbed axial flow, thereby enhancing rod vibration, with maximum amplitude reaching 189.3 m at 3 m/s flow velocity.

Currently, published literature contains limited research on experimental and analytical methods for flow-induced vibration of wire-wrapped rods in high-speed gas environments, and no refined simulation methodology suitable for engineering applications has been established. This study focuses on a single wire-wrapped rod, establishing a refined FSI analysis model that incorporates nonlinear boundary factors such as friction and gaps, and validates the fluctuating pressure and structural displacement through wind tunnel experiments, thereby developing a reliable vibration response calculation methodology.

1 Theoretical Model

Flow-induced vibration in high-speed gas environments constitutes micro-amplitude vibration. This study employs a one-way fluid-structure coupling approach for computational analysis, utilizing Star-CCM+ and Abaqus co-simulation technology. Fluid loads obtained from Star-CCM+ flow field analysis are transferred to the structural model for vibration response calculation.

Common turbulence simulation methods include Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES). RANS performs time averaging of the Navier-Stokes equations, modeling turbulent fluctuation effects as Reynolds stress terms, making it suitable for steady or quasi-steady problems. LES directly resolves large-scale eddy structures while modeling small-scale eddies, enabling high-fidelity capture of turbulent transient characteristics. Consequently, this study adopts the LES method for flow field analysis.

The core concept of LES is to partition turbulent structures into large-scale and small-scale eddies. Large-scale eddies are resolved through direct numerical simulation (DNS), while small-scale eddies are modeled using a subgrid-scale (SGS) model. The LES governing equations are obtained by spatially filtering the Navier-Stokes equations:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial \tau_{ij}^{SGS}}{\partial x_j}$$

where $\bar{u}_i$ and $\bar{p}$ represent the filtered velocity and pressure fields, respectively, and τ_{ij}^{SGS} is the subgrid-scale stress tensor representing the influence of small-scale eddies.

The wire-wrapped rod structure is a slender quasi-cylinder, allowing shear deformation and rotational inertia effects to be neglected. Its motion can be represented by transverse displacement of the axis, i.e., using Euler-Bernoulli beam theory. The free vibration equation is:

$$EI\frac{\partial^4 w}{\partial x^4} + m\frac{\partial^2 w}{\partial t^2} = 0$$

where E is the elastic modulus, I is the moment of inertia, w is the transverse displacement, and m is the mass per unit length.

Using the finite element method to discretize the structural solid, loads obtained from fluid calculations are applied to element nodes in vector form [?]. The dynamic equation is:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{f}_{fluid}$$

where $\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$, and $\mathbf{u}$ represent structural acceleration, velocity, and displacement, respectively; $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, and $\mathbf{f}_{fluid}$ is the fluid load applied to the structure in one-way FSI.

2.1 Computational Domain and Mesh

The structural model comprises a single wire-wrapped rod, a hexagonal flow channel, and upper and lower end caps. The rod is centrally located within the hexagonal flow channel, connected at the lower end to a lower end cap with 19 holes via short pins, and inserted into an upper end cap with 19 holes at the top. Geometric parameters of the wire-wrapped rod and flow channel are listed in Table 1 , and the geometric model is shown in Figure 1 [Figure 1: see original paper].

The tangential structure between the wire wrap and rod creates sharp corners in the flow field analysis, severely affecting mesh quality and computational results. Therefore, an intersecting structure approximation is adopted, with meshing at the wire-rod junction shown in Figure 2 [Figure 2: see original paper].

The fluid domain uses air. The inlet is specified as a velocity inlet boundary with a flow velocity of 60 m/s and turbulence intensity of 2%. The outlet is specified as a pressure outlet boundary with pressure set to 0 Pa. Steady-state calculations were performed, and grid independence was verified by comparing pressure drops at two measurement points located 0.1 m and 0.9 m from the inlet, as shown in Table 2 . The mean pressure drop and RMS values show minimal variation across three mesh sizes. Considering the balance between computational accuracy and efficiency, the mesh with 10.85 million cells was selected for subsequent analysis.

2.2 Flow Field Analysis Results

Large eddy simulation was employed with a time step of 0.001 s and total duration of 3 s. Velocity contours at the 3 s moment are shown in Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper]. The results reveal significant differences in fluid velocity distribution at the inlet cross-section, with high-velocity regions distributed in the hexagonal area surrounding the central rod. This occurs because the CFD model inlet boundary includes an inlet orifice plate (shown in Figure 5 [Figure 5: see original paper]), causing intense mixing at the entrance. Since fluid cannot pass through the central rod position, high-velocity regions appear in the flow domain surrounding the central rod, with velocity decreasing from the center outward. As the flow develops, turbulence gradually dissipates and the velocity distribution becomes more uniform, eventually achieving uniform flow around the central rod at the outlet cross-section shown in Figure 4b [Figure 4: see original paper].

Pressure time histories at measurement points located 0.1 m (P1), 0.2 m (P2), and 0.9 m (P3) from the inlet were extracted and subjected to spectral analysis, as shown in Figure 7 [Figure 7: see original paper]. The simulation measurement points are illustrated in Figure 6 [Figure 6: see original paper].

Flow field analysis results indicate that the dominant frequencies of fluctuating pressure concentrate in the low-frequency region, exhibiting low-frequency broadband characteristics consistent with turbulent excitation. The P1 point near the inlet contains more frequency components, while the P3 point near the outlet is dominated by low-frequency components. This demonstrates that the orifice plate structure at the inlet creates intense mixing, resulting in high turbulence and complex frequency content, which gradually dissipates as the flow develops, with frequencies becoming increasingly low-frequency dominant —a trend that aligns well with the velocity distribution. To quantify the intensity of flow field pressure fluctuations, the root mean square (RMS) values were calculated. The RMS fluctuating pressure is 37.3 Pa at the inlet (P1) and 38.9 Pa at the outlet (P3).

3.1 Fluid-Structure Coupling Model

To accurately account for boundary effects at the wire-wrapped rod inlet and outlet, solid elements were used to model the inlet pin structure, wire-wrapped rod, and outlet end cap as three separate components, as shown in Figure 8 [Figure 8: see original paper]. All materials are stainless steel with a density of 7860 kg/m^3, elastic modulus of 210 GPa, and Poisson' s ratio of 0.3.

Since the excitation forces acting on the wire-wrapped rod in the flow field are relatively small, the solid' s reaction force on the flow field does not constitute a significant influence. Therefore, one-way fluid-structure coupling was employed for numerical calculations. Based on Star-CCM+ and Abaqus co-simulation technology, the wire-wrapped rod surface was designated as the fluid-structure coupling interface, with fluid excitation loads transferred from the flow field to the structural model at each time step for vibration response calculation.

Nonlinear boundary factors were considered as follows:

Inlet: The rod is constrained at the inlet end by two parallel pins, allowing only translational movement along the pin direction. Solid pin models were created to account for pin stiffness, with friction and gap contact defined between the pins and rod holes. The gap was set to 0.05 mm, and the friction coefficient was set to 0.2 for steel-on-steel contact.

Outlet: The rod is inserted into the end cap at the outlet end, allowing axial movement and rotation through a clearance fit. A solid outlet end cap model was created to account for end cap stiffness, with gap contact defined between the rod and end cap center hole. The gap was set to 0.1 mm.

3.2 Vibration Analysis Results

Vibration response calculations employed one-way coupling co-simulation technology with the flow field, using a time step of 0.001 s and total duration of 1 s. Displacements at two measurement points on the wire-wrapped rod located 0.1 m (D1) and 0.9 m (D2) from the inlet were extracted, as shown in Figure 9 [Figure 9: see original paper].

Simulation results show that displacement amplitudes and trends at the inlet and outlet measurement points are similar, both exhibiting low-frequency, large-amplitude swinging superimposed with small-amplitude, high-frequency vibration. This is attributed to the absence of surrounding rods constraining the single wire-wrapped rod, combined with gap contacts at both ends, resulting in overall low-frequency swinging. The small-amplitude, high-frequency vibration represents typical flow-induced vibration characteristics caused by fluid pulsation. The RMS displacement is 55 m at D1 and 46 m at D2.

4. Experimental Validation

A suction-type direct-flow wind tunnel test bench was constructed for high-speed air environments. Fluctuating pressure in the flow field and acceleration/strain signals at various measurement points on the wire-wrapped rod were acquired. Acceleration signals were integrated to obtain displacement responses, enabling analysis of flow field pressure fluctuation characteristics and wire-wrapped rod vibration response features to validate the accuracy and feasibility of the computational methodology for flow-induced vibration response of a single wire-wrapped rod in high-speed gas environments.

4.1 Test Bench and Specimen

The flow-induced vibration test bench for rod bundle structures in high-speed gas environments primarily consists of an inlet section, contraction section, transition section, rod bundle test section, diffusion section, centrifugal fan, and data acquisition/processing system, as shown in Figure 10 [Figure 10: see original paper]. The test section is suspended on an isolation platform using flexible ropes, with a flexible membrane providing soft connection to the diffusion section to ensure that vibration experienced by the test specimen originates solely from flow field excitation. During testing, air enters the wind tunnel through a honeycomb and screen at the inlet, passes through a variable cross-section contraction into the test section, and is finally exhausted by the fan.

The wire-wrapped rod test specimen features a hollow thin-walled tube structure made of stainless steel, with steel wire helically wound and spot-welded onto the fuel rod. The test specimen parameters are identical to those of the numerical simulation model, with the structure shown in Figure 12 [Figure 12: see original paper].

4.2 Test Results

The test section has a total length of 1000 mm. Three fluctuating pressure sensors (P1-P3) were installed at 100 mm, 200 mm, and 900 mm from the inlet using drilled mounting in the flow channel wall. Two accelerometers were installed inside the wire-wrapped rod at 100 mm and 900 mm from the inlet, with perpendicular measurement directions: A1 measures vertical acceleration and A2 measures horizontal acceleration. The measurement point layout is shown in Figure 6 [Figure 6: see original paper].

At a fan shaft frequency of 66.0 Hz, the inlet wind speed reaches 60 m/s. Signals from the flow channel wall pressure measurement points and the two internal accelerometer measurement points were acquired to obtain time-domain curves. DC components were removed from the time-domain curves, and power frequency was eliminated using a band-stop filter. After fast Fourier transform (FFT), frequency-domain curves for each sensor at different measurement points were obtained.

Time-domain and frequency-domain test curves for fluctuating pressure are shown in Figures 13 [Figure 13: see original paper] and 14 [Figure 14: see original paper]. Displacement time-domain and frequency-domain curves obtained by integrating acceleration signals are shown in Figure 15 [Figure 15: see original paper].

Test results indicate:

1. **Fluctuating Pressure:** Pressure at the outlet exceeds that at the inlet, with a maximum RMS value of 58.5 Pa due to mixing effects from the wire wrap structure. The spectrum exhibits broadband characteristics from 5 Hz to 100 Hz, consistent with turbulent excitation features.
2. **Displacement and Acceleration:** The absence of fan shaft frequency and blade frequency signals in the spectrum demonstrates effective vibration isolation. The lack of high-frequency peaks indicates no acoustic resonance phenomena. Displacement signals are dominated by low frequencies, with RMS displacement values of 61 m at the inlet and 79 m at the outlet.

4.3 Results Comparison and Validation

Comparisons between simulation and experimental results at different locations are presented in Table 3 and Figure 15 [Figure 15: see original paper]. The comparison reveals:

1. **Fluctuating Pressure:** Numerical simulation results show consistent trends with experimental measurements at both inlet and outlet, with outlet pressure exceeding inlet pressure and similar amplitude magnitudes around 50 Pa RMS. However, simulated pressure fluctuation frequencies are lower than test results, likely because the LES subgrid-scale modeling of small-scale eddies loses some high-frequency information.
2. **Displacement:** Numerical simulation displacement amplitudes at inlet and outlet agree well with experimental values. Under 60 m/s inlet wind speed, both numerical simulation and experimental results for single wire-wrapped rod displacement RMS values are approximately 60 m, both exhibiting low-frequency dominance. However, simulated displacement

frequencies are lower, attributed to lower excitation frequencies in the simulation and the inclusion of friction and contact nonlinearities at boundaries, which dissipate high-frequency energy, resulting in lower frequency content in the simulation.

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Note: Figure translations are in progress. See original paper for figures.