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Prediction of Steam Generator Tube Behavior via Fluid-Structure Interaction Analysis

Dae Kyung Choi [a], Won Man Park [a], Young-Jin Oh [b], Sang-Hoon Lee [b], Kunwoo Yi [c], and Choengryul Choi [a]*
[a] *ELSOLTEC, Giheung-gu, Yongin, Gyeonggi-do, 16950, Korea*
[b] *KEPCO Engineering and Construction Co. Ltd.,269 Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, 39660, Korea*
[c] *Fluid System Engineering Dept. NSSS Div., KEPCO E&C, 989-111 Daedukdaero Yuseong-gu, Daejeon, Korea*
**Corresponding author: crchoi@elsoltec.com*

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1. Introduction

Nuclear power generation has two major systems, the primary and secondary systems, to convert the heat generated in the nuclear reactor into electric power [1-2]. The primary system transfers the heat from the nuclear reactor to the steam generator, and the steam generated by the transferred heat in the steam generator powers the turbine in the secondary system. Thus, the steam generator is the last part of the primary system and the first part of the secondary system.

The heat is transferred via numerous long tubes in the steam generator tube. Hot steam flows through tubes boils water flowing around tubes. Here, the fluids flowing through and around tubes can induce vibration of the tubes, and that could result in the wear or damage of tubes. Therefore, investigation of fluid-induced vibration of the steam generator tube is critical to estimate and predict their wear. In this study, we investigated fluid-induced tube vibration. Tube behaviors were predicted using fluid-structure interaction analysis.

2. Materials and Methods

Fluid-structure interaction (FSI) analysis has been widely used to investigate structural behaviors caused by fluid flows. In this study, FSI analysis, which is a combined computational fluid dynamic (CFD) and finite element (FE) analysis, was used to predict the fluid-induced vibration of the tube.

2.1 Computational fluid dynamic analysis

This study assumed a simple tube with length, inner diameter, and outer diameter of 800 mm, 12 mm, and 11 mm, respectively. Water with a 1,000 kg/m^3 density and 0.0009504 Pa-s dynamic viscosity was considered a fluid flowing surrounding the tube. CFD model for the rectangular geometry with 340 mm of width, 120 mm of height, and 800 mm of length was developed. The tube's location was assumed to be the center of the rectangle. A grid system was generated in the Ansys Workbench Mesh module (Fig. 1). Cubic element was used for the grid system. The height of the first layer surrounding the tube was set to be 0.03 mm, and a growth factor of 1.1 was used from the first to the 15th layer to satisfy the y+ value of less than 30. The size of the grid along the axial direction was set to be 2 mm.

Velocity inlet and pressure outlet conditions were applied to the left and right surfaces of the CFD model. Symmetric wall conditions were applied to the superior and inferior surfaces, and the wall condition on the tube surface was applied for the analysis conditions (Fig. 2). Then, the force on the tube surface caused by the fluid flowing with 0.4 m/s of velocity was predicted for 5 seconds. The Reynolds number was set to be 5,000.

2.2 Finite element analysis

A finite element model of a beam for simulating the tube considered in CFD analysis was developed. Springs were attached at both ends of the beam, and the springs were fixed on the ground (Fig. 3). The elastic modulus of 200 GPa, Poisson's ratio of 0.29, and density of 8,000 kg/m^3 were used for the material properties of the tube and 0.155 N/mm was applied for spring coefficient of the spring. The force calculated by CFD analysis was applied on the tube surface then the mechanical behaviors of the tube along the lift force direction (Y-direction) were predicted using FE analysis.

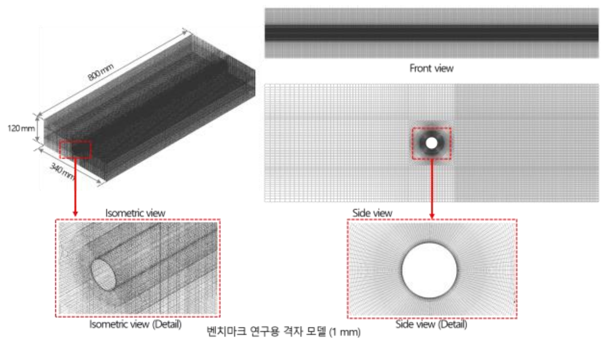


Fig. 1 CFD model of the flowing water surrounding a tube

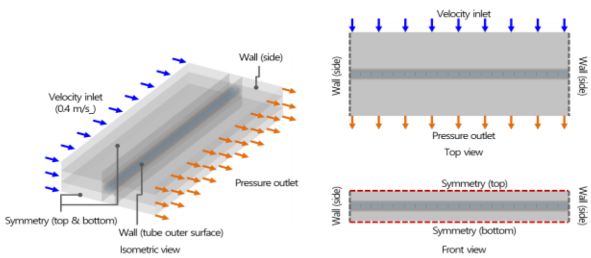


Fig. 2 CFD analysis conditions on the model surfaces

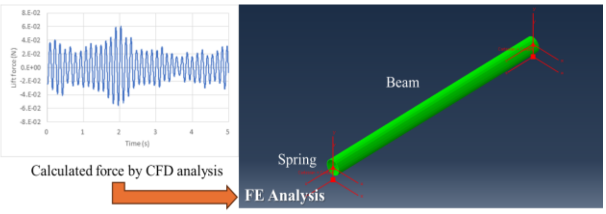


Fig. 3 FE model of a simple tube and applied load

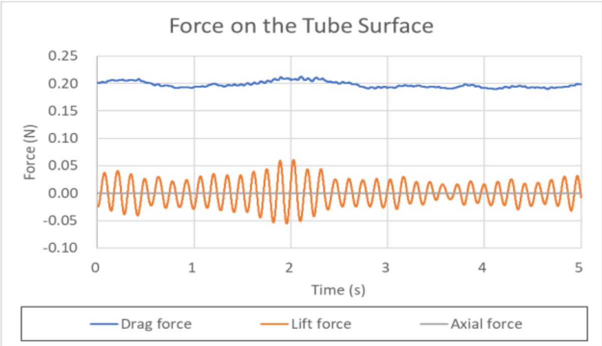
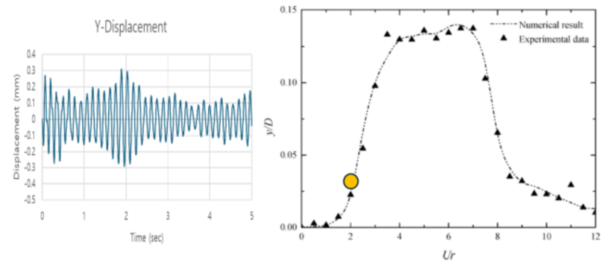


Fig. 4 The forces on the tube surface along three directions



(a) Tube displacement (b) Validation of the result

Fig. 5 Predicted displacement of the tube along Y direction

3. Results

The resultant forces on the tube surface, calculated by integrating the pressure on the tube surface, were predicted (Fig. 4). The force along the axial direction was neglectable. While the absolute value of the drag force on the tube was greater than the lift force, the amplitude of the lift force was much greater than the drag force amplitude. The maximum drag and lift forces were 0.212 N and 0.061 N, respectively. The frequency of the predicted lift force was about 7.2 Hz.

The predicted natural frequency of the tube was 16.5 Hz. However, the frequency of the lift force was far from the natural frequency of the tube. The maximum displacement of the tube was about 0.3 mm, and the frequency of tube vibration was the same as the frequency of the applied lift force (Fig. 5a).

4. Discussion

Because the frequency of the lift force by the fluid flow was different from the natural frequency of the tube, the resonance of the tube did not occur. The maximum displacement of the tube was about 0.3 mm, and the results were in good agreement with the previously published experimental and numerical results (Fig. 5b) [3].

In this study, a 1-way FSI analysis, in which the FE results were not applied to the CFD analysis, but the results of the CFD analysis adopted in FE analysis, was used to predict the mechanical behaviors of the tube. Even though the current results showed good agreement with the previously published experimental results, the motion of the tube would not be negligible when the flow velocity increases. Therefore, the authors plan to investigate a tube's flow-induced vibration using both 1-way and 2-way FSI analysis methods. Then, based on the investigations, we will determine the conditions in which 1-way FSI is acceptable.

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