

Influence of tube design and analytical parameters on steam generator tube behavior in one-way FSI analysis

Dae Kyung Choi^a, Choengryul Choi^{a*}, Won Man Park^a, Young Min Byun^a, Seung Mok Yoo^a

Young Jin Oh^b, Heejae Shin^b, and Sang Hoon Lee^b

^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

*Corresponding author: crchoi@elsoltec.com

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1. Introduction

Both nuclear and thermal power plants are types of steam power plants that generate electricity by utilizing thermal energy, which is produced from sources such as coal, gas, or nuclear fuel. This thermal energy is converted into mechanical energy through steam, which serves as the medium for transferring energy. Steam generators are therefore critical components in power plants that utilize thermal resources. In nuclear power plants, the presence of primary and secondary systems ensures nuclear safety, with heat transferred from the primary system to the secondary system to generate steam [1]. Maintaining the integrity of steam generator tubes is essential for both safety and efficient operation [2]. As high-temperature steam flows through the tubes, it induces vibrations and heat transfer interactions that may result in wear or damage. Consequently, understanding the vibrational behavior of steam generator tubes is critical for predicting tube wear and ensuring long-term reliability. Numerous experimental and numerical studies have been performed to investigate these phenomena.

In recent years, computer simulation has been widely employed to predict physical phenomena such as fluid-structure interaction, heat transfer, and vibration responses. The accuracy of such simulations is essential for ensuring credible results, yet outcomes are significantly influenced by analytical conditions, including discretization schemes and time increment settings. To address this, the present study conducted a benchmark investigation of an experimental study in which steam generator tube motion and impact force were evaluated using a combination of computational fluid dynamics (CFD) and finite element analysis (FEA). By systematically varying analytical conditions in the computer simulations, this work aims to identify the factors influencing prediction accuracy, thereby providing deeper insights into the reliability of numerical approaches for steam generator tube vibration analysis.

2. Materials and Methods

A benchmark study was performed based on the experimental work by Darwish et al. to evaluate steam generator tube vibration and impact forces [3]. The

analysis consisted of two stages: computational fluid dynamics (CFD) to obtain flow-induced forces and finite element analysis (FEA) to predict structural responses.

For the CFD stage, a rotated square array of tubes was modeled with an outer diameter of 19 mm and a pitch-to-diameter ratio of 1.64. Half-symmetry CFD model was developed for transient LES simulations. The mesh resolution satisfied $Y^+ \approx 1$, with up to 9.2 million cells for the transient model. A homogeneous Eulerian multiphase mixture model was applied with void fractions up to 60%, assuming standard air–water properties at room temperature. Inlet velocities were selected to match the normalized pitch velocity conditions of the experiment. The simulations yielded velocity fields and unsteady lift/drag forces on tube surfaces for structural loading.

For the FEA stage, a flexible tube located in the fourth row and fifth column of the array was modeled using beam elements (Fig. 2). Implicit dynamic simulations were conducted in a one-way FSI framework, using CFD-derived forces as external loads. Material properties were set to reproduce an experimental natural frequency of ~ 15 Hz, and boundary conditions reflected support clearances of 0.33 mm and 0.66 mm. Tube displacements and impact forces were obtained and compared with experimental observations to validate the numerical approach. Two different stiffness of the tube was considered and two different time increment with 1/1,000 second and 1/10,000 second were considered. The implicit FEA were conducted for 3 seconds.

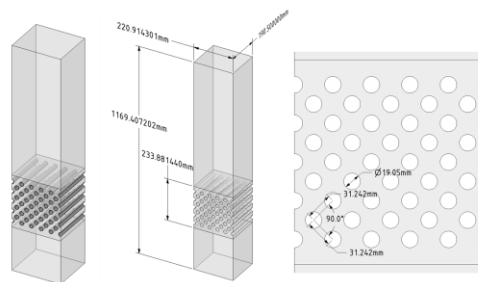


Fig. 1 3D cad model of the fluid section with rotate rectangular tube array

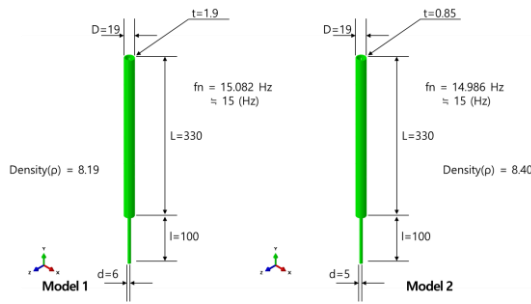


Fig. 2 Finite element model of a tube using beam elements with two different flexibility

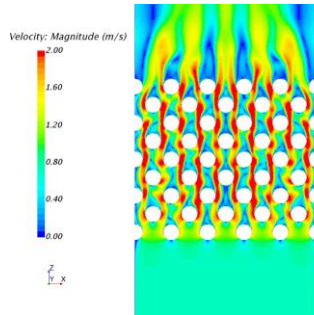


Fig. 3 Predicted fluid velocity using LES CFD analysis

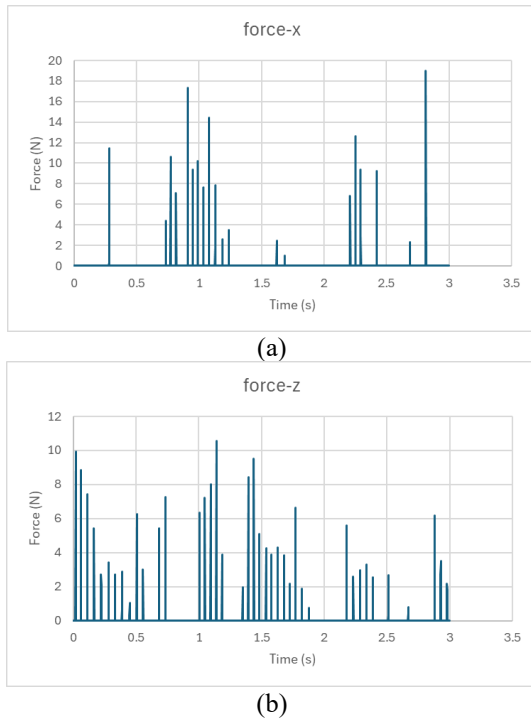


Fig. 4 Predicted contact forces when time increment of 1/1,000 was used, (a) horizontal direction and (b) the flow direction

3. Results and Discussion

From the CFD analysis, fluid forces were obtained in three directions: flow, horizontal, and axial (Fig. 3). The results were sensitive to both tube stiffness and the applied time increment. When a diameter of 6 mm was

modeled, a rattling motion with multiple contact events was observed, whereas the lower-stiffness model with a 5 mm diameter remained attached to the guide without rattling (Figs. 4 and 5). The analysis with a time increment of 1/10,000 s predicted contact forces approximately five times greater than those obtained with a 1/1,000 s increment. However, in both models, contact forces occurred more frequently in the flow direction than in the horizontal direction. These findings highlight that accurate structural modeling and appropriate selection of analysis conditions are critical for predicting tube behavior and assessing potential wear.

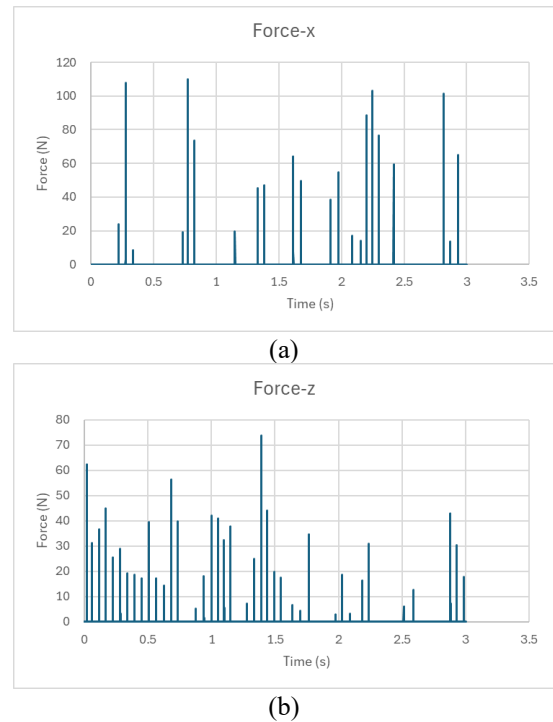


Fig. 5 Predicted contact forces when time increment of 1/10,000 was used, (a) horizontal direction and (b) the flow direction

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