Prediction of Steam Generator Tube Wear Using a Developed Finite Element Analysis Code

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***Keywords :** steam generator, tube wear, finite element analysis, Archard equation

1. Introduction

A steam generator generating steam using the transferred heat from the nuclear reactor is one of the major components of a nuclear power plant. Here, the primary system is the circuit in which the heat is transferred from the nuclear reactor to the steam generator. The secondary circuit is from the steam generator to the turbine. The steam generated by the steam generator rotates the turbine to generate electricity. These two circuits should be separated to maintain nuclear safety [1-3]. A steam generator, especially a steam generator tube, is the junction of the primary and secondary circuits. It transfers the heat from the primary circuit to the secondary one and separates the two circuits.

Therefore, the integrity of the steam generator tubes is critical regarding the efficiency and safety of nuclear power plants. However, despite its importance, it has been reported that one of the major reasons decreasing utilization rate of the nuclear power plant is damage to the steam generator tube [4]. In this study, we developed a finite element analysis code to calculate the mechanical behaviors of the steam generator tube according to the fluid flow surrounding the tube. The code was validated by comparing it to the commercial FE software. Then, the wear of the tube was estimated in the arbitrarily chosen conditions.

2. Materials and Methods

A two-dimensional finite element (FE) analysis code to predict the dynamic behavior of a beam was developed using the Newmark method in a commercial numerical computing program MATLAB 2017b (MathWorks, Natick, MA). The beam structure in the code consists of four sections, each of which could be a rectangle bar, cylinder, or tube. The beam in the code was assumed to be an Euler-Bernoulli beam. Thus, pure bending in the midplane is considered, while shear and rotational effects are neglected. In the Euler-Bernoulli beam, the curve of ω(x) describing the deflection of the beam against the applied force q is calculated as shown in the following equation,

$$\frac{d^2}{dx^2}\left(EI\,\frac{d^2\omega}{dx^2}\right) = q$$

where x, E, and I are the specific position x on the beam, elastic modulus, and the second moment of area of the beam's cross-section, respectively. Stainless steel was assumed to be the tube material; thus, 200 GPa and 8,000 kg/m^3 were applied for the material's elastic modulus of density.

In this study, a beam consisting of four different sections, rectangular slender, short cylinder, long tube, and short cylinder, was considered (Fig. 1). The natural frequency and mechanical behaviors of the beam under various loading conditions, including impact and cyclic load with two different frequencies, were calculated using the developed code in case that the end of the rectangular slender was fixed. The calculated behaviors were compared to the results of the commercial FE analysis software Abaqus/Standard (Dassault Systèmes, Waltham, MA, USA) to validate the developed code.

Then, the work rate, a key component to predict the wear of a steam generator tube, was calculated using the developed code. The volume wear rate of a tube is proportional to the normal work rate, as shown in the following equation [5],

$$\dot{V} = K \cdot \dot{W}$$

where $\dot{V}$, K, and $\dot{W}$ are volume wear rate, fretting wear coefficient, and work rate. Also, the work rate can be obtained as the following equation,

$$\dot{W} = 4 \times F_D \times \overline{y_s} \times f_n$$

where F_D, $\overline{y_s}$, and f_n are drag force, RMS behavior of the interesting location, and natural frequency. The interesting point was set to be the location of 1 inch from the fixed end.

Water (its density is set to be 1,000 kg/m3) flow around the tube with 500 mm/s of velocity was assumed. The drag and lift coefficient was set to be 0.57. The static drag and dynamic lift forces induced by the water flow were calculated based on the previously published study (Fig. 2) [6]. The natural frequency of the tube and the RMS behavior of the interesting location were predicted using the developed code. Here, we assumed the tube is located in the superior region of the steam generator, thus the tube underlying a server loading condition was considered in this study. The work rates were predicted when the flow velocities of 500 mm/s and 3,000 mm/s.

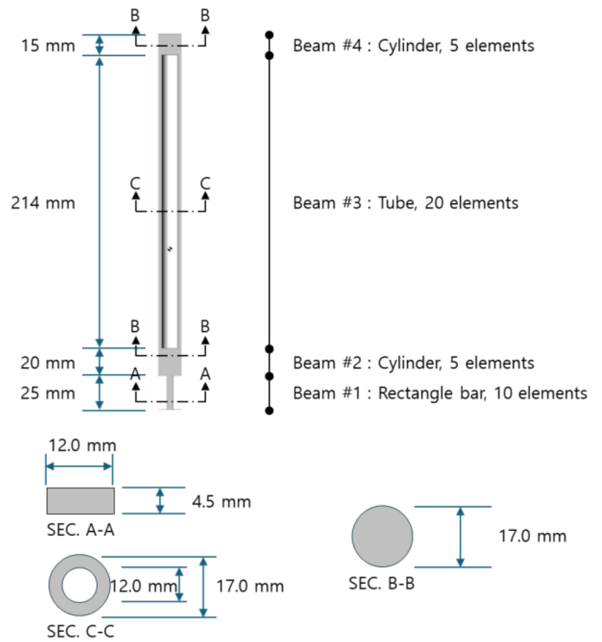
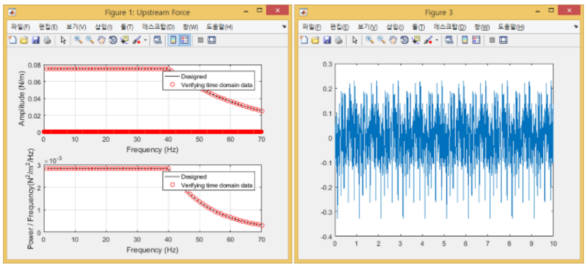


Fig. 1. Geometry of the beam structure consisting of four sections and FE model of the tube using beam elements



(a) (b)

Fig. 2. (a) Designed turbulent lift force by the flow shown in PSD and FFT, and (b) transformed time-domain force

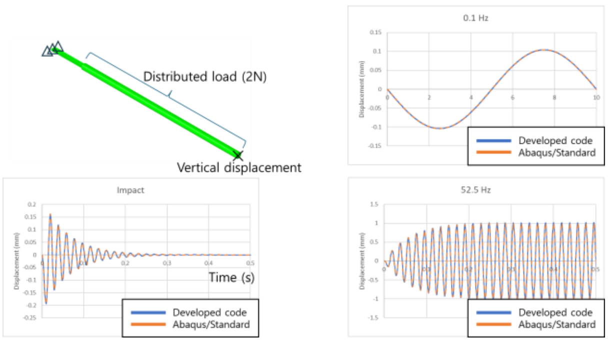


Fig. 3. (a) Designed turbulent lift force by the flow shown in PSD and FFT, and (b) transformed time-domain force

3. Results and Discussion

The predicted natural frequency of the tube in the air ambient condition by the developed code was 52.5 Hz, and it was 50.4 Hz by the commercial software. Because of the added mass effect of the ambient water [7], the natural frequency decreased to 47.5 Hz in the water ambient condition in the developed code and 45.6 Hz in the commercial software. The developed code showed only 4 % differences in natural frequencies compared to the commercial software.

The predicted mechanical behaviors by the developed code showed good agreement with the results of the commercial FE software Abaqus/Standard (Fig. 3). The Euler-Bernoulli beam was considered in this study. However, the predicted results by the commercial software using the Euler-Bernoulli beam or the Timoshenko beam also well matched the results by the developed code. Thus, the authors concluded that the developed code was validated in the aspects of predicting the mechanical behaviors of the tube.

The RMS displacements at the interesting point by the dynamic lift force were 1.23 μm and 44.3 μm when the fluid velocity was assumed to be 500 mm/s and 3,000 mm/s, respectively. Thus, the work rates were calculated as 70.6 μJ/s and 91.5 mJ/s accordingly. In this study, the work rates of a tube were predicted in the arbitrarily chosen conditions. In future studies, the authors plan to obtain an optimal fretting wear coefficient and validate the developed code by comparing it to the experimental results. The authors believe the results of this study could contribute to predicting steam generator tube wear and maintaining its integrity.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20224B10100030).

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