1. INTRODUCTION

In Korea, since the first nuclear power plant was built in 1978, 22 plants have been running, playing an important role by generating about 23% of total domestic electric power. In the case of the steam generator of Gori-1, which was exchanged in 1989, various types of corrosion have been experienced such as pitting, SCC (stress corrosion cracking), and wear, etc. The succeeding plants also have had various types of corrosion problems though this is now better managed [1].

Vibrations generated by fluid have three causes: fluid-elastic instability, forced vibration with unsteady pressure fluctuation originating from turbulence, and the periodic vibration with vortex shedding on the heat pipe around the steam generator can cause the wear or the fatigue fracture, finally resulting in the failure of SG (steam generator) [2]. Cracks of heat pipe and TSP (tube support plate) caused by various microscopic factors like chemicals and sludge deposits [3], but one of the primary factors to consider is fretting wear [4] in the combination of the tube and TSP.

In this research, we studied a simplified U-tube model for further simulation in the future. An experimental reduced scale model of a U-shaped heat pipe with experiment and analysis of the investigation into fluid-structure interaction (FSI). The material of the pipe was cut from the real heat pipe of a material named Inconel 690 alloy, now used in steam generators. The accelerations at the fixed stations on the outer surface of the pipe model are measured in the series of time history, and Fourier transformed to the frequency domain. The natural frequency of three leading modes were traced from the FFT data, and compared with the result of a numerical analysis for unsteady, incompressible flow. The corresponding mode shapes and maximum displacement are obtained numerically from the FSI simulation with the coupling of the commercial codes, ANSYS-FLUENT and TRANSIENT_STRUCTURAL. The primary frequencies for the model system consist of three parts: structural vibration, BPF (blade pass frequency) of pump, and fluid-structure interaction.

2. METHODS OF RESEARCH

2.1 Numerical Method

The pressure drop is directly related to surface roughness, which is a function of the Reynolds number and the roughness ratio, defined as the ratio between roughness and tube diameter. For the analysis of primary water,
three-dimensional unsteady incompressible Navier-Stokes equations are used:

$$
\nabla \cdot \mathbf{V} = 0 \tag{1}
$$

$$
\rho \left( \frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} \tag{2}
$$

In Eqs. (1~2), $\mathbf{V}$ is velocity vector; $p$ is pressure; $\rho$ and $\mu$ are density and viscosity, respectively. No-slip boundary condition is applied at the tube wall; the inlet condition is specified as a mean flow rate and a given fluctuation; the outlet boundary is set as the ambient pressure. Additionally, $k-\omega$ SST (Shear Stress Transport) turbulence model is used for the turbulent intensity of 5% for the incident flow [5].

For the analysis of the structural dynamics of the tube, the following equations are used [6]:

$$
- \mathbf{C} : \mathbf{V} = \mathbf{f}_V \tag{3}
$$

where the elastic stiffness matrix is defined as

$$
\mathbf{C} = \frac{E}{(1+\nu)(1-2\nu)}

\begin{bmatrix}
1-\nu & \nu & 0 & 0 & 0 \\
\nu & 1-\nu & \nu & 0 & 0 \\
\nu & \nu & 1-\nu & 0 & 0 \\
0 & 0 & 0 & 0.5-\nu & 0 \\
0 & 0 & 0 & 0 & 0.5-\nu \\
0 & 0 & 0 & 0 & 0
\end{bmatrix} \tag{4}
$$

In Eqs. (3~4), $\mathbf{f}_V$ is the external force per unit volume, which is integrated from the fluid pressure at the wall; $E$ and $\nu$ are Young’s modulus and Poisson’s ratio (which should be constant in this study) respectively. The time rate of strain is expressed with the velocity components of tube elements.

$$
\frac{\partial \mathbf{\varepsilon}}{\partial t} = \frac{1}{2} \left( \nabla \mathbf{V} + (\nabla \mathbf{V})^T \right) \tag{5}
$$

In Eq. (5), the velocity components on the right hand side can be obtained from the structural deformation from the strain field. Fig. 1 is the procedure for the computation of fluid-structure interaction. The finite element model uses shape and node information in common. Under the boundary conditions, the flow field is computed, and then the effective mass distribution is exerted onto the tube structure for the consideration of the mass of internal and external fluid. After the common nodal points are set for the data exchange between fluid and structure, the system coupling to both sides is used in every time step in Eqs. (1~5) to describe the deformation of structure.

### 2.2 Surface Roughness

For a straight tube with a constant inner diameter and a cross-sectional shape, the correlation of the Darcy friction factor, $f$ with the Reynolds number and roughness ratio, $\varepsilon/d$ [7].

The plot of Eq. (6) is given in given in the Moody chart in Fig. 2. This correlation is valid only for the rigid pipes without vibration or deformation of the wall. By changing the parameters, we can obtain the numerical values of Fig. 2 where ANSYS-FLUENT is used for numerical computation.

The result is very sensitive to the grid scale, especially the vertical size of the first grid, $\Delta y$, which is expressed with a dimensionless parameter:

$$
y^+ = \Delta y \sqrt{\frac{\rho u_T}{\mu}} \tag{7}
$$

where $u_T$ is the transformed velocity component of the tangential direction of the wall. To get the proper values coinciding with Eq. (6) in the parametric plane of Fig. 2, the dimensionless wall distance should be guaranteed as $y^+<1$ in the whole computational domain. For example, when the computational domain is a pipe of 20 mm di-
ameter and 2 m length, 1,023,678 tetrahedral elements with smooth inflation at the wall should be used for each computation of Fig. 2 at least \( y^+ \approx 0.3 \). The convergence should be checked during the computation until the normalized error falls under the tolerance of \( 10^{-5} \).

### 2.3 Pressure Drop

The performance of U-tubes usually used in steam generators are listed in Table 1. From the geometry data, we composed a standard full-scale model for the computation of fluid: Fig. 3. In the classical theory, the pressure drop directly depends on the Darcy friction factor, \( f \):

\[
\Delta p = \frac{\rho g h_f}{2} = f \frac{L}{d} \left( \frac{V^2}{2} \right)
\]

where \( V = \|V\|_2 \) in the radial mean; \( L \) and \( d \) are length and diameter of pipe, respectively [7]. However, additional pressure loss should occur in the bended corner of the pipe.

Fig. 4(a)–(d) shows the velocity distributions at the four cross sections marked in Fig. 3. The roughness ratio, \( \varepsilon/d \) lies in the range of 10 to 200 times the regular value in Table 1. As the roughness increases, the maximum velocity at the center increases because the boundary layer becomes thicker. The centrifugal force at corners deforms the velocity

<table>
<thead>
<tr>
<th>Material</th>
<th>Inconel Alloy 690 (Ni 60%, Cr 30%, Fe 10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size and surface roughness</td>
<td>External diameter: 19.05mm (±0.1 mm), Thickness: 1.07 mm, Length: max 27.4 m, min 15.4 m (mean 20.7 m), Surface roughness: inside 0.5 ( \mu )mRa, outside 1.6 ( \mu )mRa</td>
</tr>
<tr>
<td>Tube shape</td>
<td>U-shaped dune (bending radius R:76.2~279.4 mm)</td>
</tr>
<tr>
<td>Mechanical properties</td>
<td>Density: 8,190 kg/m(^3), Young's modulus: 211 GPa, Poisson's ratio: 0.289</td>
</tr>
</tbody>
</table>

Fig. 3. Full Scale Model

Fig. 4. Flow Velocity Distribution
(V, vertical to lines) profile to ones asymmetric, and the positive sign of \( r \) indicates the inner direction. To obtain these results, 4,191,063 tetrahedral elements were used for each computation. The mean value of flow velocity is 6 m/s under the operating condition.

In Fig. 5, the correlation for pressure drop, or the difference of static pressure between inlet and outlet, is a function of the roughness ratio for the present system, in a linear regression form, such as

\[
\frac{\Delta p}{\frac{1}{2} \rho V^2} = 2435 \left( \frac{\varepsilon}{d} \right) + 15.76
\]  

(9)

2.4 Experimental Model

Thanks to the supply of real U-shaped heat pipes from KEPCO NF, the experimental setup in Fig. 6 could be built in the department of Mechanical Engineering at Kunsan National University. As the full-scale system is very large (see Fig. 3), the model is reduced to about 1/4 scale. With centrifugal pump, Hanil PSS 120-096, the water is circulated from the water reservoir which is 300x600x350, size in mm, and then the U-tube is fixed vertically, linked to a closed loop under the ambient condition. The volume flow rate is measured with a vortex flow meter located in the inlet of the U-tube. The geometrical dimensions and the conditions of restriction are given in Fig. 7 together. Table 2 is the summary of the boundary conditions for the analysis of flow.

Before the main experiment, we verified the B&K accelerometer by a free hammer impact test. The vibration signal was measured at the top of tube with the accelerometer sensor, and converted to PC data with NI myDAQ board. LabVIEW is used for board control and data acquisition. The amplitude of vibration level, \( L_v \) in the unit of dB is defined as

\[
L_v (dB) = 20 \log_{10} \frac{a}{a_0}, \quad a_0 = 2 \times 10^{-5} \text{ m/s}^2
\]  

(10)

The time history data is transformed to the frequency domain with FFT (fast Fourier transformation) [8].

Before the main experiment with the configuration of Fig. 7, we conducted a pre-test on the structure of the empty U-tube, by hanging it by a rope from the ceiling of laboratory. Hitting with a light hammer, the vibration of the tube was measured at the sensor location. Table 3 shows that the measured value and its corresponding simulation with ANSYS-TRANSIENT_STRUCTURAL result in a good agreement for first and second modes drawn in Fig. 8. The relative error is within 6.5%.

Fig. 9 shows a change of natural frequencies when we tested the U-tube with and without water filled inside the pipe. The ends of the tube were not yet plugged at this point. As the water increases mass, the resultant peak frequency of each mode will decrease. The first mode, for example, moves from 107 to 92 Hz (14% reduction).
3. RESULTS AND DISCUSSION

3.1 Frequency Analysis

For the vibration signal, the acceleration is measured at eight locations marked in Fig. 10 where the coordinates in (x, y) are given in Table 4. The FFT data are shown in Fig. 11(a)~(e).

The location (a) data is given in Fig. 11(a) with the comparison of stationary fluid and moving water flow cases. With a pump of 3,400 rpm of rotational rate, the BPF (blade pass frequency) is calculated for a five-bladed rotor (n = 5) such as:

\[
\omega = 3,400 \times \frac{2\pi}{60} \text{ rad/s}
\]

\[
f_0 = \frac{\omega}{2\pi} = 56.7 \text{ Hz}
\]

\[
\therefore f = nf_0 = 284 \text{ Hz}
\]

![Fig. 8. Structural Modes](image)

![Fig. 9. Signal Processing of Measured Data](image)

![Fig. 10. Locations for Measurement](image)

![Table 3. Natural Frequencies of Structural Pre-Test](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>( f ) (Hz), experiment</th>
<th>( f ) (Hz), computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>107</td>
<td>106</td>
</tr>
<tr>
<td>2</td>
<td>199</td>
<td>186</td>
</tr>
</tbody>
</table>

![Table 4. Coordinates of Each Location](image)

<table>
<thead>
<tr>
<th>Location</th>
<th>x (mm)</th>
<th>y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>(b)</td>
<td>0</td>
<td>700</td>
</tr>
<tr>
<td>(c)</td>
<td>0</td>
<td>1,300</td>
</tr>
<tr>
<td>(d)</td>
<td>100</td>
<td>1,600</td>
</tr>
<tr>
<td>(e)</td>
<td>300</td>
<td>1,600</td>
</tr>
<tr>
<td>(f)</td>
<td>410</td>
<td>1,300</td>
</tr>
<tr>
<td>(g)</td>
<td>410</td>
<td>700</td>
</tr>
<tr>
<td>(h)</td>
<td>410</td>
<td>300</td>
</tr>
</tbody>
</table>
and can therefore be regarded as the primary frequency of fluid-structure interaction. Consequently, the peak frequencies consist of three major components: the structural homogeneous vibration, BPF of flow from the pump, and the fluid-structure interaction.

3.2 Mode Shape

The mode shape can be plotted from the numerical

<table>
<thead>
<tr>
<th>Mode</th>
<th>$f$ (Hz), experiment</th>
<th>$f$ (Hz), computation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66</td>
<td>49</td>
</tr>
<tr>
<td>2</td>
<td>124</td>
<td>111</td>
</tr>
<tr>
<td>3</td>
<td>177–209</td>
<td>252</td>
</tr>
</tbody>
</table>

In Fig. 11(a), the trail of BPF of Eq. (11) and its harmonics can be traced from FFT data by comparison with and without water flow. However, this component of forced frequency vanishes at other locations.

From Fig. 11(b) to (e), the FFT signal at the location (a)–(h) shows some common peak frequencies that are physically meaningful. The three structural leading-mode frequencies are found in Table 5 and are compared with the computational values. The first and second frequencies sometimes are decayed in location (b), (c), (e), and (g), but the third one is distributed across a broad bandwidth. Although experiment and computation do not coincide with each other exactly, the trend shows that these modes are from the characteristics of structure. The cause of error is thought to be caused by imperfect restrictions, turbulent dissipation, and signal noise in the experiment.

It should be noted that the frequency, 372–375 Hz that is independent of BPF, is often found in the FFT plots,
of a U-tube used as the heat pipe in a steam generator of the PWR. This is often suspected to be the key cause for fretting wear and cracks in pipes and TSP's. The surface roughness should expedite these kinds of causes, accelerating the corrosion of the inner surface and the fretting wear of the outer surface.

With a commercial code, ANSYS, a multi-physical simulation was done for the present problem, and a reduced-scale experimental model was set for comparison and validation with the computational result. To consider surface roughness and pressure drop, ANSYS-FLUENT code was tuned to the proper grid level with empirical correlations such as a Moody chart. For the full-scale model, a correlation of pressure drop with the surface roughness ratio has been derived from the results of the flow analysis.

The natural frequencies of structures were analyzed with FFT data in the experiment. The water-induced source of forced vibration is from the pump feeding the primary water to the system. The BPF could be traced in the FFT signal measured on the experimental model. A significant frequency of 372~375 Hz for the fluid-structure interaction has been extracted from the experimental result, which should be verified in the future. The vibration frequency is composed of: 1) structural vibration, 2) pump BPF, and 3) interaction in the ascending order of values, and all of them are in the listenable range. Three leading mode shapes have been shown by the computation, which supplies a reasonable physical interpretation in spite of a degree of error in the experiment. As the maximum deformation of a pipe is about four times the roughness of the inner surface, it is predicted that the structural deformation is in the order of one digit larger than the roughness in the conventional Inconel 690 tubes of the full-scale model. The surface roughness inside a brand-new tube is 0.5 μm, and the corresponding maximum displacement was predicted as 2.0 μm (0.002 mm), for example. However, from the view point of endurance, it is possible that contamination or corrosion of the inner surface can increase the surface roughness from tens to hundreds of times.

With an understanding of the complicated nonlinear physics involved, the results of this study can be used as the basic data for the prediction of fluid-structure interaction, and for the effect of pressure drops caused by the roughness of inner surfaces of U-tube systems in a steam generator.

**ACKNOWLEDGEMENT**

This research was supported by 1) the Energy Technology Development program (Grant No. 2011150100060) and 2) the Human Resources Development program (Grant No. 20124010203240) of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grants funded by the Korea government Ministry of Trade, Industry, and Energy.
REFERENCES


