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Fluid-elastic Instability Evaluation of Steam Generator Tubes

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Abstract : It has been reported that the plugged steam generator tube of Three Mile Island Unit 1 in America was damaged by growing flaw and then this steam generator tube destroyed the nearby steam generator tubes of normal state. On this account, stabilizer installation is necessary to prevent secondary damage of the steam generator tubes. The flow-induced vibration is one of the major causes of the fluid-elastic instability. To guarantee the structural integrity of steam generator tubes, the flow-induced vibration caused by the fluid-elastic instability is necessary to be suppressed. In this paper, the effective velocity and the critical velocity are calculated to evaluate the fluid-elastic instability. In addition, stability ratio value of the steam generator tubes is evaluated in order to propose one criterion when to determine stabilizer installation.

Key words : steam generator tube, fluid-elastic instability, stability ratio, stabilizer, anti-vibration bar

1. Introduction

Current operating procedures of the steam generators of nuclear power plant include that the steam generator tubes should be plugged when the amount of wear reaches 40% of the thickness of the steam generator tubes. But it has been reported that the plugged steam generator tube of Three Mile Island Unit 1 in America was damaged by growing flaw and then this steam generator tube destroyed the nearby steam generator tubes of normal state [1]. On this account, stabilizer installation is necessary to prevent secondary damage of the steam generator tubes.

The flaw of the plugging steam generator tubes can continue to grow by the flow-induced vibration. The flow-induced vibration is one of major causes of the fluid-elastic instability. When the stability ratio exceeds more than 1, the vibration amplitude of the steam generator tubes increase rapidly by the fluid-elastic instability [2]. Rapid increase of the vibration amplitude causes the damage of the steam generator tubes. When the steam generator tube contacts to AVB (anti-vibration bar), the tube thickness decreases and the radioactive coolant can leak in severe cases.

In this paper, the effective velocity and the critical velocity are calculated to guarantee the structural integrity of steam generator tubes by the fluid-elastic instability evaluation. In addition, the fluid-elastic instability of the steam generator tubes is evaluated in order to propose one criterion when to determine stabilizer installation.

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2. Modal Analysis

2.1 Three-dimensional steam generate tube

The modal analysis is performed using the software ANSYS (V. 12.0) [3]. The steam generator tube is modeled using three-dimensional beam elements (Beam4) and the tube supporting points are modeled using combination elements (Combin40). The supporting points are comprised of AVB and TSP (tube support plate). The U-bend region is supported by AVB and the straight region is supported by TSP. Generated gap data [4] are used at the supporting points of a steam generator tube. Fig. 1 shows the finite element model used in the analysis. The necessary data of the steam generator tubes is obtained from EPRI report [5]. Table 1 shows the data of the steam generator tubes.

2.2 Modal analysis

Natural frequencies and vibration modes are obtained using the three-dimensional finite element models of steam generator tubes. In order to consider the effect of the gap at the supporting points, one model is made without considering gap, and the other model is made

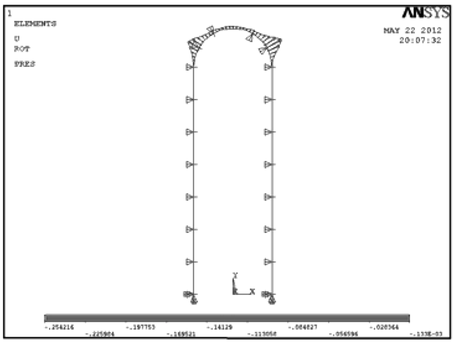

Fig. 1. FEM model of the steam generator tube.

Table 1. The data of the steam generator tube.

Conditions	Data
Element	Beam4
Tube diameter	0.875 in
Tube wall thickness	0.025 in
Young`s modulus	28500000 psi
Density	0.305 lb/in^3
AVB stiffness	11000 lb/in
TSP stiffness	84000 lb/in
Height in straight region	350.875 in
Height in U-bend region	59.838 in

with the generated gap values. The effect of the fluid inertia is also examined. Fig. 2 shows the boundary conditions of the steam generator tube model when the gap is not included. Fig. 3 shows the boundary conditions of the steam generator tube model when the gap is included.

When analyzing natural frequency, the fluid inertia should be considered. If a suitable method exists, we can use the method. But if any suitable method does not exist, virtual density of the steam generator tube can

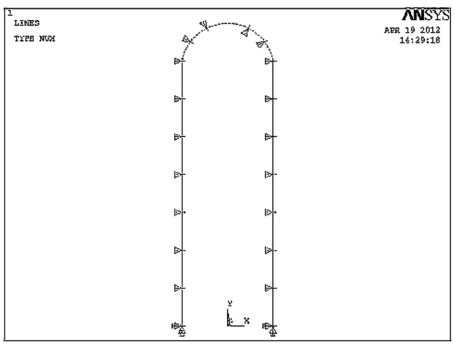

Fig. 2. Boundary conditions of the steam generator tube without gap.

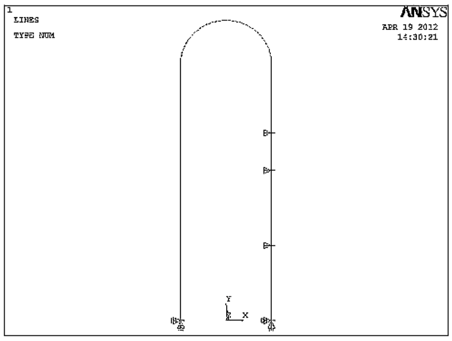

Fig. 3. Boundary conditions of the steam generator tube with gap.

be used. The virtual density is defined as follows [6].

$$\rho_v = \overline{W}/(gA_t) \tag{1}$$

Here $\overline{W}$ is the tube virtual density and defined by the following equations (2) and (3). For the vertical region of the steam generator tube, it is defined as the following equation (2).

$$\overline{W} = A_t\rho_t + A_i\rho_1 + 3.1A_0\rho_2 \tag{2}$$

For the U-bend region, it is defined as the following equation (3).

$$\overline{W} = A_t\rho_t + A_i\rho_1 + 1.7A_0\rho_2 \tag{3}$$

Here ρ_t is tube virtual density, ρ_1 is average primary fluid density, ρ_2 is secondary fluid density at outermost tube bundle radius. A_t, A_i and A_0 is expressed as the following equation (4).

$$\begin{aligned} A_t &= \pi(R_0^2 - R_i^2) \\ A_i &= \pi R_i^2 \\ A_0 &= \pi R_0^2 \end{aligned} \tag{4}$$

The parameter values used in the analysis are presented in Table 2.

Table 3 shows the obtained natural frequency values when the fluid density effect is not included in the model. The lowest natural frequency is 37.2 Hz when the gap is not included and 0.385 Hz when the gap is included.

Table 4 shows the natural frequency values when the fluid density effect is included in the model. The lowest natural frequency is 34.0 Hz when the gap is not included and 0.366 Hz when the gap is included.

From the result, it is noted that natural frequency can

Table 2. The parameters of the steam generator tube.

Parameter	Value
R_0	0.4375 in
R_i	0.4125 in
A_t	0.06676 in
A_i	0.5346 in
A_0	0.6013 in
ρ_t	0.305 lb/in^3
$\overline{W}$	0.04098 lb/in

Table 3. Natural frequency of the steam generator tube without fluid inertia.

mode	Frequency (Hz)	
	Without gap	With gap (gap values case 1)
1	37.184	0.38479
2	37.22	0.77013
3	37.389	1.0482
4	37.426	1.6642
5	41.609	1.8873
6	41.713	3.6249
7	42.198	3.6475
8	42.318	5.9597
9	48.301	5.9645
10	48.51	8.3958

Table 4. Natural frequency of the steam generator tube with fluid inertia.

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vary dramatically according to the existence of gap at the supporting points. Figs. 4 and 5 show the first mode shapes of the steam generator tubes when the gap is not considered and considered respectively. In both cases

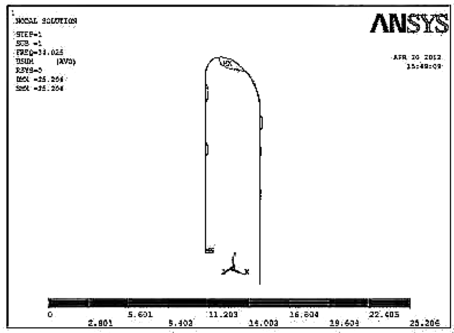

Fig. 4. The first mode shape when the gap is not considered and the fluid inertia effect is considered.

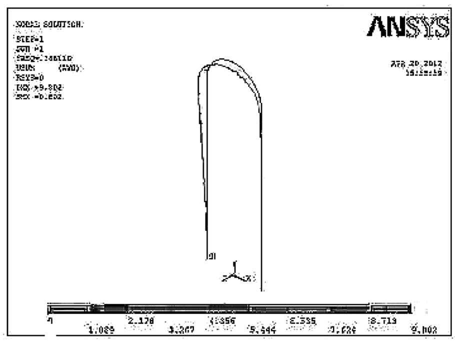

Fig. 5. The first mode shape when the gap and the fluid inertia effect are considered.

the fluid inertia effect is considered

3. Fluid-elastic Instability Evaluation

3.1 Calculate the effective velocity

If the cross-flow occurs over a partial span or only one span of multi-span tube, the effective full span velocity must be determined since the critical velocity is based on full span flow. The effective velocity is expressed as the following equation (5) [7].

$$V_{\mathrm{eff}}^2 = \int(\rho(x)/\rho_0)V^2(x)\phi^2(x)dx \Big/ \int(M(x)/M_0)\phi^2(x)dx \tag{5}$$

Here $V(x)$ is cross-flow velocity-spanwise variation, ρ_0 is secondary fluid density, $\rho(x)$ is spanwise variation in secondary fluid density, $\phi(x)$ is spanwise variation in normalized modal displacement, M_0 is tube mass per unit length and $M(x)$ is spanwise variation in tube mass per unit length.

$V(x)$ and $\rho(x)$ distributions used in the analysis are plotted in Figs. 6 and 7 [5]. $\phi(x)$ is obtained from the modal analysis.

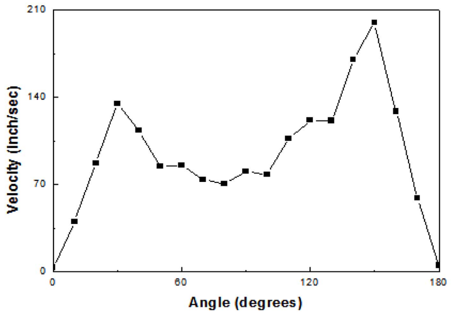

Fig. 6. Velocity distribution in U-bend region [5].

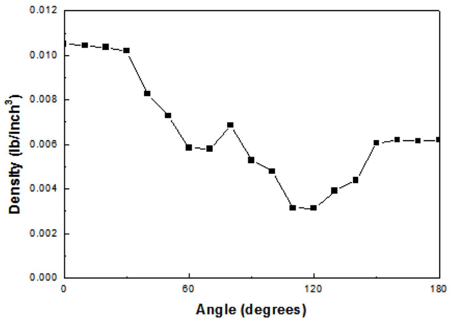

Fig. 7. Density distribution in U-bend region [5].

3.2 Calculate the critical velocity

The critical velocity is expressed as the following equation (6) [8].

$$V_{cr} = kf_n d(m_0 \delta_0 / \rho_0 d^2)^{1/2} \quad (6)$$

Here k is instability constant, f_n is span natural frequency of Steam generator tube, d is outer diameter, m_0 is tube virtual mass, δ_0 is $2\pi\zeta$, ζ is critical damping ratio and ρ_0 is secondary fluid density.

Damping ratio distribution is given in Fig. 8 [5]. The k value is determined by the tube array. Table 5 shows the k values according to tube array [7]. f_n values are given in Tables 3 and 4. The used ρ_0 value is 0.00657 lb/in. and m_0 can be calculated using the values in Table 2.

3.3 Fluid-elastic instability evaluation

The phenomenon of fluid-elastic instability is observed when the absorbed flow energy is larger than the dissipated energy through damping. In other words, fluid-elastic instability would arise if the stability ratio exceeds more than 1. When the steam generator tubes are designed, the stability ratio should be less than 0.75. Therefore, the stabilizer installation may be necessary when the stability ratio exceeds 0.75. The stability ratio is defined as the following equation (7).

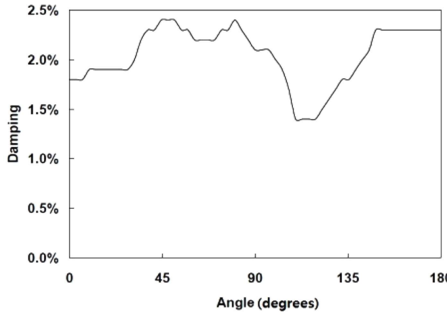

Fig. 8. Damping ratio distribution in U-bend region [5].

Table 5. Instability constant k.

Tube array	Square array	30 ° array	60 ° array
k values	7.1	4.9	3.2

$$SR = V_{eff} / V_{cr} \quad (7)$$

Here V_{eff} is the effective velocity, V_{cr} is the critical velocity.

Table 6 shows the stability ratio values when there is no gap at the supporting points. For the first vibration mode, SR is 0.481 when the fluid inertia is not considered and SR is 0.480 when the fluid inertia is considered. For all vibration modes, SR values are less than 0.75. So for this particular calculation case, stabilizer installation is determined to be unnecessary because all stability ratios are less than 0.75.

4. Conclusion

To guarantee the structural integrity of steam genera-

Table 6. Stability ratio in the steam generator tube without gap.

Cases	SR values	
	Without fluid inertia	With fluid inertia
Mode 1	0.481	0.480
Mode 2	0.527	0.531
Mode 3	0.571	0.436
Mode 4	0.524	0.581
Mode 5	0.41	0.523
Mode 6	0.471	0.474
Mode 7	0.507	0.42
Mode 8	0.462	0.517
Mode 9	0.381	0.461
Mode 10	0.348	0.412

tor tubes and to propose one criterion for determining stabilizer installation, modal analysis and the fluid-elastic evaluation of the steam generator tubes are conducted using the finite element method. The results are as follows:

[1] The natural frequency and vibration mode can be changed due to the existence of the gap at the supporting points.

[2] The stability ratios were calculated from the fluid-elastic instability evaluation and they show the values less than 0.75. Therefore, for the particular case, the stabilizer installation is determined to be unnecessary.

Acknowledgments

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