Experimental and Analytical Investigation of Natural Vibration of Steam Generator Heat Transfer Tube

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1 INTRODUCTION

S.G. heat transfer tubes may be failed due to flow-induced vibration in shell side, then the heat transfer efficiency of tube bundle is decreased. In the severest condition, the trip accident shall be happened. Therefore, the research of vibration mechanism and structural measure is a important problem in reactor technology.

A lot of research works about heat transfer tube had been performed at home and abroad (Chen, S.S. 1972,1973; Elliott, G.L. et al, 1973; Shin, Y.S. et al 1977; Liangbi, Han et al, 1985).

The object of our work was engineering application, the consideration of clearance and real supporting condition. In the first step, the preliminary test about spring constants were performed. Finally, the computed results were compared with the corresponding experimental data.

2 NATURAL VIBRATION TEST OF THE MODELLED HEAT TRANSFER TUBES

2.1 Test rig

Figure 1 test model

The test rig is shown in figue 1. A stiff frame was used instead of S.G. vessel. The interaction of neighbouring tubes were modelled by 7-row tubes. The geometric dimensions, supporting condition, tube arrangement, piths and quatrefoil holes of supporting plates, clearances & anti-vibration bars are same as prototype S.G. tube bundle.

2.2 Measurement system and method

The measurement system are shown in figure 2. The resonanse method was used. The exciting signal were sine waves or white noise.

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Based on the vibration character of plane U-tube, its normal modes are divided into four kinds, i.e in-plane symmetric, in-plane anti-symmetric, out-of plane symmetric and out-of plane anti-symmetric. The coupling effect not exist. So that, each of the four kinds of normal modes can be measured separately.

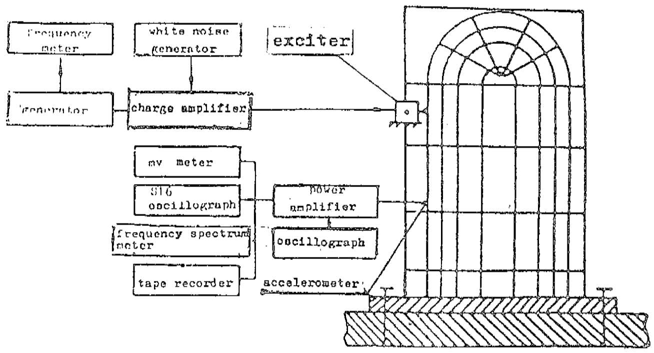

Figure2 measurement system of natural vibration test

3 ANALYSIS OF NATURAL FREQUENCIES AND NORMAL MODES OF THE HEAT TRANSFER TUBES

The boundary conditions of heat transfer tubes were considered as clamped at the tube sheet, as simple supported at the supporting plates, as simple supported for out-of plane motion and elastically supported for in-plane motion at the anti-vibration bars.

3.1 Determination of the elastic constants

For the in-plane motion of the heat transfer tubes, the elastic constants can be determined by using a two spans continuous beam with same supporting conditions as the bend of heat transfer tubes. In figure 4(a), the normal mode equation for the single span beam is

$$y = a\cos kx + b\sin kx + c\,\mathrm{ch}\,kx + d\,\mathrm{sh}\,kx \qquad (1)$$

$$x=0,\quad EIy'''\big|_{x=0} = -\beta_0 y\big|_{x=0} \quad EIy''\big|_{x=0} = \alpha_0 y'\big|_{x=0} \qquad (2)$$

$$x=l,\quad y'=y'''=0 \quad \text{for odd rank,}$$

$$x=l,\quad y=y''=0 \quad \text{for even rank.} \qquad (3)$$

From equation (1)-(3) the frequency equations of single span beam with elastically supported are obtained.
for odd rank,

$$\frac{2\beta_0}{EIk^3} - \left(1 - \frac{\alpha_0\beta_0}{E^2I^2k^4}\right)(\mathrm{tg}kl + \mathrm{th}kl) - \frac{2\alpha_0}{EIk}\mathrm{tg}kl\,\mathrm{th}kl = 0 \qquad (4)$$

for even rank,

$$\frac{2\beta_0}{EIk^3} + \left(1 - \frac{\alpha_0\beta_0}{E^2I^2k^4}\right)(\mathrm{ctg}kl - \mathrm{cth}kl) + \frac{2\alpha_0}{EIk}\mathrm{ctg}kl\,\mathrm{cth}kl = 0 \qquad (5)$$

where

$$k=\sqrt{2\pi f\sqrt{\frac{m}{EI}}} \qquad (6)$$

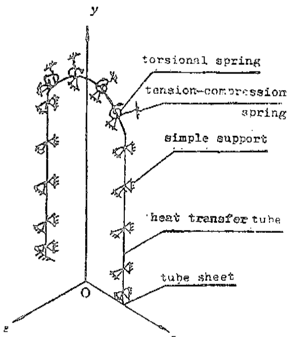

Figure 3 supporting condition of heat transfer tube

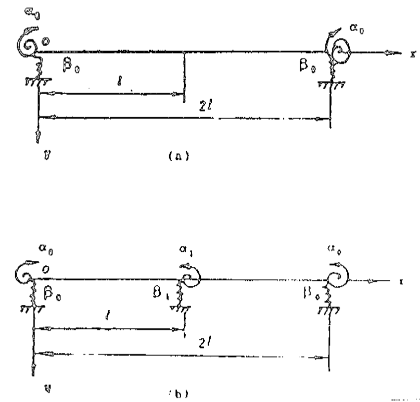

Figure 4 determination of elastic constant of single span & two spans beam.

Using (4)-(6) with experimental data of the single span beam, we can obtain the corresponding value of α_0 and β_0.

In figure (6), using the symmetry for the middle boundary condition of the two span continuous beam, we can obtain.

$$x=l,\quad EIy'''\Big|_{x=l}=\beta_1 y\Big|_{x=l},\quad EIy''\Big|_{x=l}=-\alpha_1 y'\Big|_{x=l} \qquad (7)$$

$$\frac{\beta_0}{EIk^3}\left\{\frac{\alpha_0}{EIk}\left[\left(1+\frac{\alpha_1\beta_1}{E^2I^2k^4}\right)+\left(1-\frac{\alpha_1\beta_1}{E^2I^2k^4}\right)\cos kl\,\mathrm{ch}k+\frac{\alpha_1}{EIk}(\cos kl\,\mathrm{sh}kl+\sin kl\,\mathrm{ch}kl)+\frac{\beta_1}{EIk^3}(\sin kl\,\mathrm{ch}kl-\cos kl\,\mathrm{sh}kl)\right]+\left(1-\frac{\alpha_1\beta_1}{E^2I^2k^4}\right)\times(\cos kl\,\mathrm{sh}kl-\sin kl\,\mathrm{ch}kl)+\frac{2\alpha_1}{EIk}\cos kl\,\mathrm{ch}kl+\frac{2\beta_1}{EIk^3}\sin kl\,\mathrm{sh}kl\right\}-\left(1-\frac{\alpha_1\beta_1}{E^2I^2k^4}\right)\sin kl\,\mathrm{sh}kl+\frac{\alpha_1}{EIk}(\cos kl\,\mathrm{sh}kl-\sin kl\,\mathrm{ch}kl)+\frac{\beta_1}{EIk^3}(\cos kl\,\mathrm{sh}kl+\sin kl\,\mathrm{ch}kl)=0 \qquad (8)$$

Using (6) and (8) and two experimental values of natural frequency for two spans continuous beam, α_1 and β_1 can be obtained.

3.2 The calculation of the natural frequencies of heat transfer tubes for S.G.

The tube element and boundary element (Bathe,K.J. et al) were applied and the precision of the natural frequencies was compared. The results of the analytical method and FEM for U-bend and the straight segement are in good agreement. The computed natural frequencies are divided into four types of the normal modes.This phenomenon shows the same stiffness for the four types of the normal modes.

Besides, at the middle point of the U-bend there are some features as follows:

1. For in-plane symmetric normal modes, the horizontal displacement and rotation about Z axis are equal to zero, i.e. $u_x=0, \theta_z=0$.

2. For in-plane anti-symmetric normal modes, the vertical displacement is equal to zero, i.e. $u_y=0$.

3. For out-of plane symmetric normal modes, the rotation about

y axis is equal to zero, i.e. $\theta_y = 0$.
4. For out-of plane anti-symmetric normal modes, the horizantal displacement of Z direction and the rotation about x axis are equal to zero, i.e. $u_z = 0$, $\theta_x = 0$.

4 EXPERIMENTAL AND COMPUTED RESULTS

4.1 The natural frequencies of the heat transfer tubes in air

The experimental and computed natural frequencies of the typical heat transfer tubes are shown as table 1 and table 2.

table1. The natural frequencies of model tubes in out-of plane (Hz)

normal mode	model tube 1		model tube 2	
N	measured	computed	measured	computed
1	41.3	40.4	41.9	41.1
2	41.3	40.5	43.7	41.2
3	51.6	52.2	50.7	54.0
4	54.1	52.7	56.5	54.1
5	66.9	63.7	65.4	71.2
6	70.9	69.1	68.4	71.2

table2. The natural frequencies of nodel tubes in in-plane (Hz)

normal mode	modeltube 1		model tube 2	
N	measured	computed	measured	computed
1	42.9	40.3	39.7	41.5
2	48.9	41.8	45.0	42.3
3	51.6	51.3	54.3	54.4
4	57.1	55.0	59.6	56.3
5	65.6	66.6	66.4	71.2
6	71.3	70.7	69.3	72.7

4.2 The effect of the clearance between supporting plate and tubes

The effect of the clearance between supporting plate and tubes was studied. The test results indicate that the response bands become broader. There are some high frequency components in the response spectrum, the exciting frequency are more dominant. The relation between displacement and acceleration is

$$(dB)_x = (dB)_a - 4n \qquad (9)$$

Where $(dB)_x$ and $(dB)_a$ are the decibel numbers of displacement amplitude and acceleration amplitude respectively, n is the ordinal number of 1/3 frequency range of the central frequency in the dynamic frequency spectrum meter.

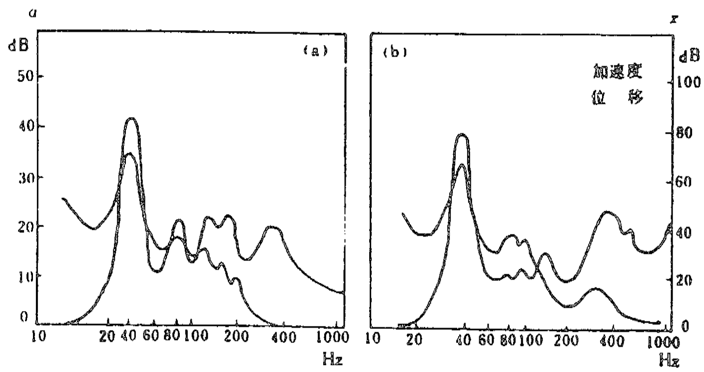

Figure 5 The response spectrum of the model tube 1
(a) in-plane f =42.9Hz (b) out-of plane f =41.3

5 CONCLUSION

After experimental and analytical investigation, the natural vibration character of the heat transfer tube can be concluded as follows:

1. The structual measure of anti-vibration bars for the U-bend of the heat transfer tubes is necessary for increasing the structual stiffness in out-of plane.

2. The interaction of the tubes is negligible, the natural frequencies of the different heat transfer tube with the different U-bend radii can be studied separatedly.

3. The experimental data of the straight tube excited from different directions were same, which show that: at 0.5-0.6mm clearances between supporting plate and tubes, the function of quatrefoil holes were same as the function of circlar holes. The boundary conditions of heat transfer tubes at supporting plates were simple supported.

4. Appearing the high frequency components, the response bands become broader due to the existence of clearance between supporting plates and tube. In the same time, the impact phenomenon will happen(YiKang, Dou et al,1986).

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