An Experimental Investigation of Fluid-Elastic Instability in Two-Phase Cross-Flow

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1. Introduction

The U-bend region of nuclear steam generator tubes which undergoes high flow two-phase flow condition is highly susceptible to flow-induced vibration. In various flow-induced vibration mechanisms, it is generally known that fluid-elastic instability is the main cause of fretting wear of U-tubes.

Most of the previous experiments were performed with tube bundles which had triangular or normal square arrays and p/d ratio under 1.5. The U-bend region of KSNP (Korea Standard Nuclear Power Plant) steam generator has rotated square array with p/d of 1.633, which needs additional fluid-elastic instability experiments.

Fluid-elastic instability characteristics in air-water two-phase cross-flow have been experimentally investigated using three different arrays of straight tube bundles. Rotated triangular (RT) array tube bundle with p/d of 1.47 is for the counterpart test of existing work. Rotated square (RS) and normal square (NS) array tube bundles with p/d of 1.633 are for the investigation of fluid-elastic instability features in KSNP steam generator.

The present paper provides the experimental results of tube vibration response, damping ratio, hydrodynamic mass, and fluid-elastic instability.

2. Experiments

2.1 Test Apparatus

The test section has cross-sectional dimension of 88×600 mm. As working fluids, air and water of atmospheric pressure and room temperature are injected at the bottom part of the test section. Each tube bundle is assembled with brass tube which has length of 600 mm, diameter of 12.7 mm, and thickness of 0.89 mm. Each cantilevered tube can vibrate in a cantilevered mode (flexible tube) or in a both side clamped mode (rigid tube). The tube bundle with all flexible tubes (flexible tube bundle) is used for the tests to find the onset of fluid-elastic instability, and the tube bundle with single flexible tube surrounded by rigid tube (rigid tube bundle) is used for the tests to measure the damping ratio and the hydrodynamic mass. More detailed information on the test apparatus and an experimental procedure can be found on reference [1].

2.2 Experimental Results

When the homogeneous gap velocity is low, tube vibration responds show the turbulence-induced excitation characteristics. The tube vibration amplitude is similar both in drag and lift directions or slightly larger in drag direction, and the increase rate of RMS tube displacement with regard to the gap velocity is not significant.

Above a certain gap velocity, the RMS tube displacement shows a sharp increase with respect to small increase in the gap velocity, which can be defined as the critical gap velocity of fluid-elastic instability. In the case of RT and NS arrays, the sharp increases of tube displacement are found in lift direction.

On the contrary, fluid-elastic instability is found in drag direction in RS array, and the tube displacement in lift direction is low even for the very high gap velocities.

The most unique feature of the tube vibration motion in RS array with p/d of 1.633 is that the tube-to-tube interaction due to the hydrodynamic coupling between neighboring tubes is much weaker in two-phase flow condition, comparing to the single phase water flow in the same RS array and the two-phase flow in RT array with p/d of 1.47 and NS array with p/d of 1.633.

Total damping ratio was evaluated using half power frequency band method. Power spectral density (PSD) function was obtained from 30 min record of time domain vibration waveforms.

As shown in Fig. 1, the damping ratio was strongly dependent on the void fraction as noted by Pettigrew et al. [2], and it has the maximum of 4~5% at the void fraction of 60~70%.

Figure 2 shows the measured hydrodynamic mass ratio in RT, NS, RS tube bundle arrays, and compares the present results with Pettigrew et al.'s data [2] and theoretical values. The present hydrodynamic mass data in RT array agree well with the data of Pettigrew et al. [2].

The hydrodynamic masses in RS array are much lower than those in RT and NS arrays, which means lower liquid hold-up around tubes. This may have some relationship with the weak tube-to-tube hydrodynamic coupling in RS array with p/d of 1.633.

The most general method to predict the fluid-elastic instability would be Connors' relation which can be formulated in terms of dimensionless "reduced velocity" and "mass damping parameter" as the following equation:

$$\frac{V_{g,c}}{fD} = K\left(\frac{2\pi\zeta m}{\rho D^2}\right)^n \qquad (1)$$

As were the results of Pettigrew et al. [3], the present results obtained in RT array (p/d = 1.47) showed two regions of instability. In addition, the transition between two fluid-elastic instability regions was closely related with flow regime transition. In the case of NS array (p/d = 1.633), K and n had the value of 6.0 and 0.5, respectively. The effect of flow regime transition on the fluid-elastic instability behavior was not significant. In the case of RS array (p/d = 1.633), K and n had the value of 9.0 and 0.5 for void fraction of 60~70 %. The higher value of K was probably due to the weak tube-to-tube hydrodynamic coupling in two-phase flow condition in the present RS array.

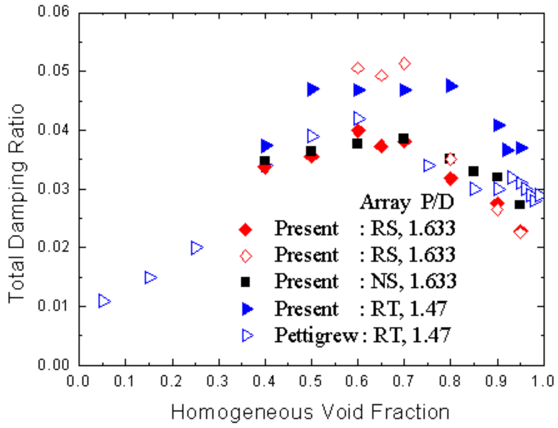

Fig. 1 Total damping ratio (for RS array, ◆: 1/2 of critical gap velocity, ◇: 1/4 of critical gap velocity)

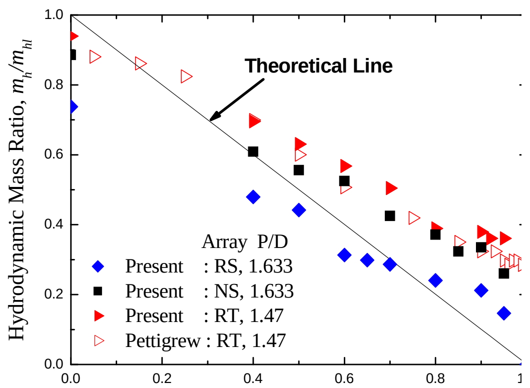

Fig. 2 Hydrodynamic mass ratio

3. Conclusion

Tube vibration response in NS and RT arrays showed strong tube-to-tube hydrodynamic coupling as the gap velocity reached the critical gap velocity. On the other hand, the hydrodynamic coupling between neighboring tubes was very weak in RS array.

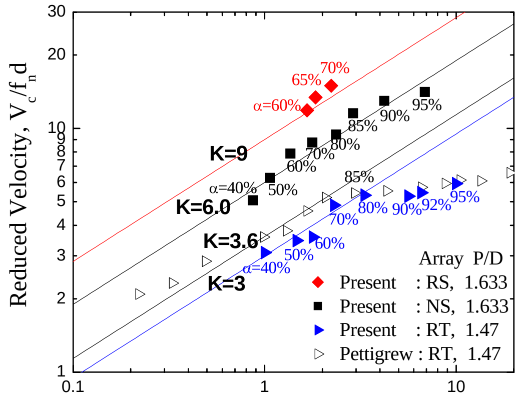

Fig. 3 Fluid-elastic instability results

The total damping ratios in three tube bundles were very dependent on the void fraction, and had the maximum at void fraction of 60~70%. The hydrodynamic mass ratios in RS array were much lower than those in NS and RT arrays, which might be related with the weak hydrodynamic coupling in RS array.

Fluid-elastic instability in RT array showed two-regions of instability, and the transition between two fluid-elastic instability regions was closely related with flow regime transition. The effect of flow regime transition on the fluid-elastic instability behavior was not significant for the NS tube array with p/d of 1.633. The higher value of K was probably due to the weak hydrodynamic coupling in two-phase flow condition.

REFERENCES

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