Fluid-Elastic Instability of Rotated Triangular Array Tube Bundle in Two-Phase Cross-Flow

I.-C. Chu, Y. J. Yun, H. J. Chung
Korea Atomic Energy Research Institute, 150 Dukjin-dong Yusong-gu Daejon 305-353 Korea, chuic@kaeri.re.kr

1. Introduction

U-bend regions of nuclear steam generator tube bundle have been experienced fretting wear damage due to two-phase cross-flow fluid-elastic instability.

Among many existing experiments, Pettigrew et al.'s works[2] are worthy of attention. They found that above a certain void fraction critical flow velocities for the fluid-elastic instability were much lower than expected by the typical Connors' correlation. They explained that the above phenomenon is probably due to the flow regime transition from continuous to intermittent flow.

However, such a fluid-elastic instability behavior with much lower critical flow velocities at intermittent flow conditions has not been clearly observed through other's experiments yet. Thus, it is the field that needs a further investigation.

The main objectives of the present experiments are to investigate the flow regimes and the resultant fluid-elastic instability behaviors in a wide range of void fraction and to cross-check the effect of the intermittent flow.

2. Experiments

2.1 Test Apparatus

As working fluids, air and water of atmospheric pressure and temperature are used. The two-phase flow channel has the cross-sectional dimension of 88 × 600 mm. Cantilevered tube bundle is inserted into the rectangular flow channel at the downstream of about 1000 mm from the air and water injection point. A mixer and homogenizer are installed at the upstream of tube bundle to provide a uniform and homogeneous two-phase cross-flow.

Tube bundles have three different arrays of rotated triangular, normal square, and rotated square, and two different P/D of 1.47 and 1.633. Brass tubes are assembled for each tube bundle array, having length of 600 mm, diameter of 12.7 mm, and thickness of 0.89 mm. Half-tubes are installed on both side walls of the flow channel to minimize the wall effects. Visual observation of the flow condition is possible through the both side walls and tube end wall (the opposite of cantilevered side).

Each tube can vibrate in a cantilevered mode (flexible tube) or in a both side clamped mode (rigid tube). Tube bundle with all flexible tubes is used for the tests to find the onset of fluid-elastic instability, and tube bundle with one flexible tube surrounded by rigid tubes is used for the tests to measure the damping ratio and the hydrodynamic mass.

The tube vibration response was measured with a pair of orthogonally installed strain gages: each for the vibration measurement in drag and lift direction, respectively. The flow regime between tube-to-tube gap was measured by a pair of ultrasonic transducers. Each transducer was installed inside a neighboring tube, and they operated in a through-transmission mode[3].

2.2 Experimental Results

In the present paper, the experimental results are provided obtained only for the tube bundle of rotated triangular array with P/D of 1.47. Tests for the onset of fluid-elastic instability and the damping ratio were performed at the void fraction of 40 ~ 95%.

The natural frequencies of 20 flexbile tubes in air were measured using 3-axis miniature accelerometer, and mean value and standard deviation were 21.4 Hz and 0.2 Hz, respectively.

Two-phase mass flux was increased in sufficiently small steps until the RMS vibration amplitude was sufficiently high to indicate the fluid-elastic instability, while keeping the homogeneous void fraction unchanged. The critical gap velocity for each void fraction condition was obtained at the condition of the fluid-elastic instability.

Measurements of damping ratio in two-phase cross-flow were carried out about half the mass flux for the fluid-elastic instability conditions. Power spectral density function was obtained from 30 min record of time domain vibration waveforms. Total damping ratio was evaluated using half power frequency band method. The measured total damping ratio was strongly dependent on the void fraction as noted in some existing works[1]. The total damping ratio had the maximum of about 4.5% at the void fraction of 50 ~ 80% condition. The damping ratio in single phase air and water flows was about 0.2% and 0.6%, respectively. In addition, measured hydrodynamic mass ratio agreed well with the result of Pettigrew et al.[1].

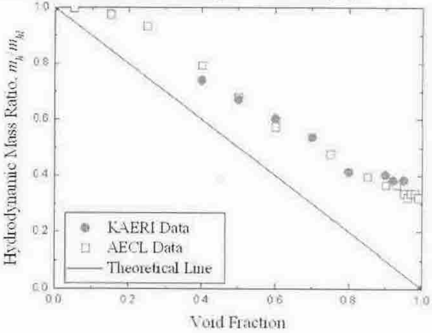

Figure 1. Hydrodynamic mass ratio: comparison between theory and experimental results of KAERI & AECL.

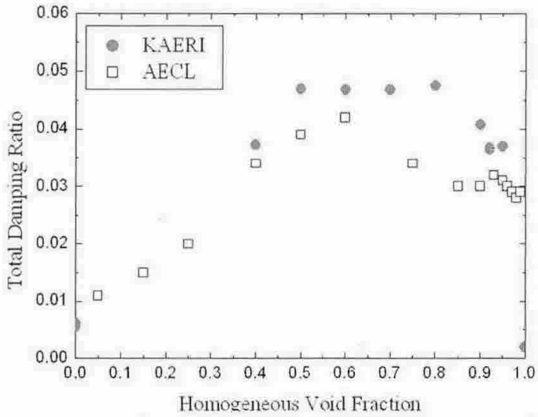

Figure 2. Damping ratio in two-phase cross-flow.

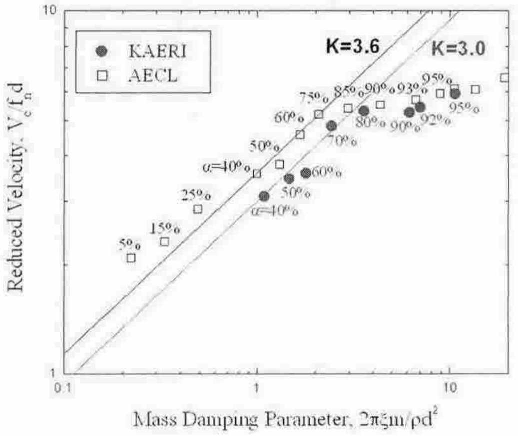

Figure 3. Fluid-elastic instability results in two-phase cross-flow.

Dimensionless "reduced velocity" and "mass damping parameter" were calculated for each void fraction condition, and then the instability factor (K) and the exponent of mass damping parameter (n) were obtained. As was the results of Pettigrew et al., the present results showed two regions of instability. The first region corresponds to lower void fraction region, and n and K have the value of about 0.5 and 3.0 as can be expected from Connors' correlation for single phase flow. In other region at higher void fraction, n has much lower value of around 0.1. In latter region, the critical flow velocities were much lower than predicted by the Connors' correlation of former region. The transition condition between two fluid-elastic instability regions corresponds to the void fraction of approximately 80%. The flow regimes measured by ultrasonic through-transmission technique showed three different regimes, namely bubbly, transitional, and intermittent. The flow regimes below the void fraction of 70% and above the void fraction of 80% are identified as bubbly flow and intermittent flow, respectively. The flow regime at the void fraction of 70~80% is identified as transitional flow between bubbly to intermittent, which agrees with the transition condition of fluid-elastic instability.

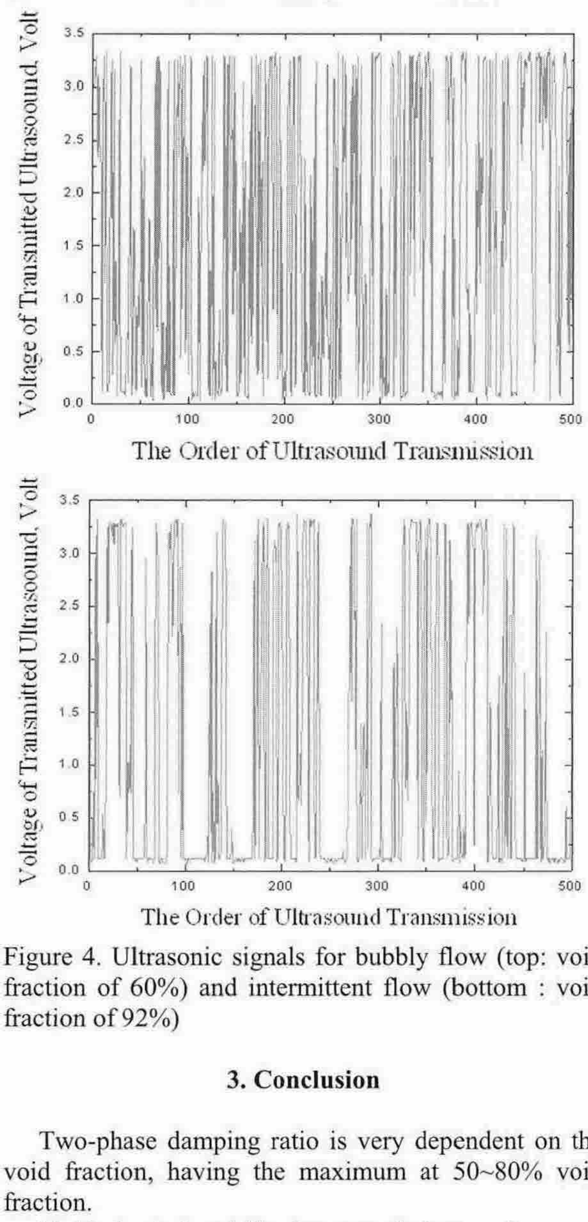

Figure 4. Ultrasonic signals for bubbly flow (top: void fraction of 60%) and intermittent flow (bottom : void fraction of 92%)

3. Conclusion

Two-phase damping ratio is very dependent on the void fraction, having the maximum at 50~80% void fraction.

Fluid-elastic instability has two distinct regions, and the transition is very closely related with the flow regime according to the ultrasonic measurement results. In the case of intermittent flow, critical velocity for fluid-elastic instability was much lower than expected.

REFERENCES

[1] M. J. Pettigrew, C. E. Taylor, and B. S. Kim, "Vibration of Tube Bundles in Two-Phase Cross-Flow: Part 1 – Hydrodynamic Mass and Damping," Trans. ASME, J. Pressure Vessel Technology, Vol. 111, p. 466, 1989.

[2] M. J. Pettigrew, J. H. Tromp, C. E. Taylor, and B. S. Kim, "Vibration of Tube Bundles in Two-Phase Cross-Flow: Part 2 – Fluid-Elastic Instability," Trans. ASME, J. Pressure Vessel Technology, Vol. 111, p. 478, 1989.