Bended zone tube assembly vibration of coiled steam generator under downward flow

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1. Introduction

Over 60 years history of the power reactor operation has demonstrated that flow-induced vibrations (FIV) of structural components can negatively affects on integrity of many plants system and reactor internals [1]. Different from commercial PWR steam supply system, Korean integrated modular reactor system utilizes tube bundles of coiled tube geometry for steam generator (SG). This coiled SG tubing has a unique geometrical configuration that smoothly transforms a vertical straight tube array into a coiled one at upper and lower part of SG inside. To measure vibration of bended zone tube array of the coiled SG under simulated flow condition, laboratory scale experimental tests program was carried out, described in this paper as following. The outcome of test program will be used for the physical understanding of complex vibration behaviors of coiled SG tubing and the analysis model verification.

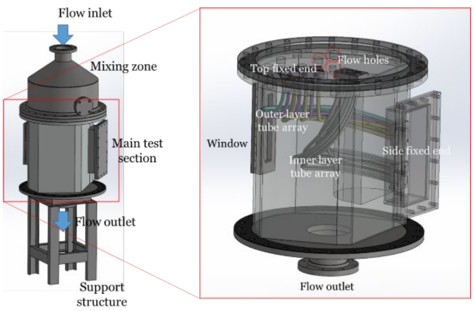

Figure 1. Schematics of Test Section.

2. Experimental Setup

The test facility was constructed to investigate the FIV characteristics of the two sets of bended tube assembly configuration for the SG. For the test, a small-scale water circulation loop was built to meet test requirement enough (145 % of design flow rate at rated temperature) of the reference reactor system design specification as shown in Fig. 1. As a working fluid, single-phase pure water was used. The maximum flow rate covered the predesignated test condition of whole FEI test program. Circulation pump is controlled to maintain desired flow rate for FIV tests. Flowmeter is placed between the pump and test section to measure inlet flow rate running into the test section. Test section is designed to make downward flow inside the test section and uniformly distribute over the tube array, other than jet flow impinging region. Two types of tube arrays (3x3 array of 15~17 outer layer, 3x3 array of 1~3 inner layer) was placed inside the test section. Test section is firmly mounted on the supporting portal frame, fixed at the structural frame of the building. Upper part of the test section is a mixing zone to expand flow region. There are several flow holes under the mixing zone to simulate equivalent diameter mixing holes in the actual SG part. The locations of holes are adjusted to be uprightly above test tubes to put fast flow on those tubes. Target flow rate was controlled by the motor-driven inverter control. The system pressure of the test loop is balanced in constant value at the outlet port by the pressurizer unit. Bended test tubes were fabricated into a finite length by machining and firmly connected to the mounting plate with variable orientation. Both ends of the tubes are the firmly mounted on the upper and side wall of the test section.

3. FE Modal Analysis and Test Result

Modal analysis using ABAQUS was performed for the test tube array. Fig. 2 and Table 1 show the FE model and mode analysis results. Results shows the decrease in frequency of tubes under water by added mass effect. In order to simulate the tube dynamics, the pipe element (PIPE22) and mechanical properties of Inconel 690 was used. The boundary conditions are fixed one at both ends. The tubes of selected layers were analyzed. The added mass theory [1] was applied to obtain the natural frequencies of the tubes in water.

Table 1. Natural frequencies of 15^{th} – 17^{th} layer tubes

Layer	Row	1^{st} frequency	2^{nd} frequency	3^{rd} frequency
15	1	139.35	322.30	325.61
	2	92.519	217.11	241.00
	3	66.825	157.91	185.16
16	1	110.63	261.85	286.00
	2	77.886	187.26	217.53
	3	59.147	139.95	168.17
17	1	89.836	218.82	251.57
	2	65.285	158.55	189.07
	3	50.643	118.86	144.94

Note) added mass effect included

Fig. 3 shows typical vibration response waterfall charts of instrumented bended tubes during the continuous flow sweeping test condition, combined with graphical representation of the measurement location and corresponding log-scale color map along the indication arrow. Outer-side located bended tube 16-1 and 16-2 shows relatively simple pattern and inline-spikes of dominant periodic components, compared to the inner located tubes.

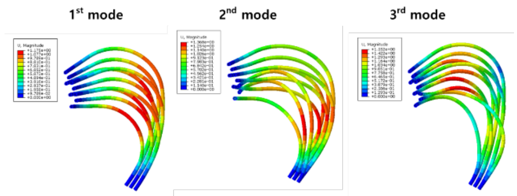

Figure 2. FE model and mode shapes for coiled SG tube 15th – 17th layers (deformation scale factor : 40.0).

Peak components in measured response spectrum were mostly identified as their tube's fundamental and second natural frequencies. Within the log scale plots of each figure in the color map, there are some lower amplitude signals of incremental pump harmonics, likewise an order tracking of the rotating shaft. But their contribution of weak harmonics from pump rotation to structural vibration of bended tubes can be treated as negligible effect with respect to the linear scale vibration response. But steam generator designer should keep in mind that there are always the periodic components in the measured spectrum of vibrating structure in contact with the flow, from pump-rotation-driven harmonics and blade passing frequency.

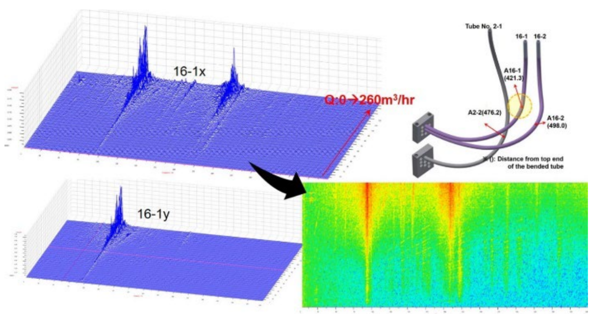

Figure 3 Typical Vibration response waterfall during flow-varying transient test condition, combined with graphical representation of the measurement location and log scale color map.

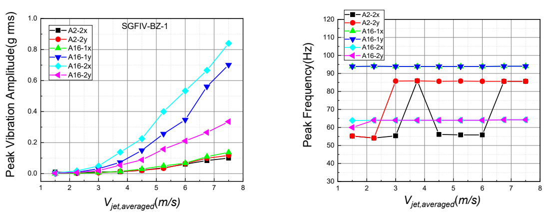

Fig. 4. normalized vibration response and peak frequency of the bended zone along the flow velocity.

All responses in Fig. 3 are transient responses which means that the flow was continuously changing with constant sweeping speed of 52 m^3/hr a minute (sweeping rate: 0~260 m^3/hr for 5 minute). Interested thing to note is that the side frequency band of peak periodic components has gradually increasing trends, in adverse with sharp spikes at the lower flow velocity. One can figure out that increase of the averaged flow velocity somewhat contribute to increase vibration damping of the bended tube array.

Figure 4 shows typical vibration response amplitude and peak frequency variation of the bended zone tubes along the flow velocity, during the steady-state flow test condition. Each dot in the Fig. 4 are extracted from the most dominant peak component of the measured response spectrum. From the figures above, there are no symptoms of turning trends in vibration response amplitude and in significant frequency variation (near at maximum flow velocity) along the increasing test flow trip. These experiment results will support that there is no possibility of FEI for bended zone tube array over normal operation of steam generator. The outcome of test program will be used for the physical understanding of complex vibration behaviors and the analysis model verification.

4. Conclusion

Preliminary FE analysis for the bended zone tube array showed that selected boundary condition by tube end's weldment in experimental setup realized closer natural frequency to real bended tubes and can provide more conservatism on the vibration frequency matching.

Bended zone test setup is geometrically-more realistic representation of steam generator tubing than the sectional-wise test one. Thus, result data-sets from the bended tube test showed much closer look to the real engineering problem and applications, compared to that of the section-wise bundle test [2]. But the limitation of bended tube test setup is clear due to the lack of test tube number to be included and two different arrays combined into one single test chamber, which is very different with the real operating environment. From the whole test program and comprehensive measurement, we concluded that there is no possibility of FEI for bended zone tube array even in two times higher than the flow velocity of normal operation

REFERENCES

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[2] Kang-Hee Lee, Heung-Soek Kang, Du-Ho Hong, Jong-In Kim, 2023, Fluidelastic instability of a curved tube array in single phase cross flow, Nuclear Engineering and Technology, 55, pp. 1118-1124.