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Fluidelastic instability of staggered tube arrays with preferentially flexible direction to single phase cross flow: typical results

K.-H. Lee [a*], H.-S. Kang [a], D.-S. Oh [a], C. Lee [a], I.-S. Im [a], C.-H. Shin [a], S.W. Lee [a], T.-H. Chun [a], S.-H. Kim [a], J.-I. Kim [b], C.-H. Ha [b], D.-H. Hong [b], M.K. Cho [b]

[a]*KAERI, 111, 989 bungil, Deaduk-dero, Yusung-gu, Daejeon, Korea*
[b]*DHIC, 22, DoosanVolvo-ro, Seongsan-gu, Changwon, Gyeongnam, Korea*
[*]Corresponding author: leekh@kaeri.re.kr

1. Introduction

Flow-induced vibrations (FIV) of the internal system components in nuclear power plants can cause system failure and safety issues. Fluidelastic instability (FEI) is one of the most critical FIV mechanism to steam generator commissioning and licensing [1]. Eight steam generator (SG)s of Korean indigenous SMR design are located in the annulus region between core support barrel and the reactor pressure vessel. Each SG has 376 helically coiled tubes in 17 layers and its internal tubing composes of upside/downside bending region and mostly coiling region in the middle. Korean SG vendor needs essential design data as well as resolve some technical issues during the preliminary design to advance toward detail design and manufacturing, based on the design guideline [2]. KAERI started the experimental R&D project named as flow-induced vibration and wear testing of steam generator helical tubing. Here in this paper, the critical of velocity for FEI of given staggered tube arrays were measured in preferentially flexible direction to single phase cross flow. The orientation of the tube vibration follows the naming rule of traditional SG tube FEI testing in the out-of-plane(OOP) and the in-plane(IP). One should keep in mind that vibration plane of Korean SMR SG tubing is opposite against the traditional one, because of the helical coiled SG tube design.

2. Experimental overview

The test loop(SGFIV Test Loop) for the straight tube bundle FEI testing consists of the main circulation pump, water storage tank, flow meter, and test section as shown in Figure 1(P&ID drawling of the loop and sectional view of the test section). The main circulation pump of 34 kW can circulate a maximum flow rate of 180 m^3/hr. The maximum rotation speed of the pump having five blades is 3600 rpm. The flow rate into test section can be controlled by an inverter and a bypass line. The storage tank is equipped with a diaphragm so that the discharge wave does not propagate to the suction of the pump. The storage capacity of the tank is about 2.5 ton. An ultrasonic water flow meter was installed in the loop for accurate flow-rate monitoring. The fluid temperature is monitored with a thermocouple in the test loop.

The test section, holding test tube assembly over the mounting plate, is installed between two vertical H-beam supports. The single phase demi-water flow is passing downward through test section. Reinforcement was provided by vertical beams support and horizontal steel frame structures at the top and bottom of the test section. The inlet and outlet of the test section are connected by flexible tubes to reduce vibration in the main loop.

Test tubes are designed to vibrate in preferentially flexible orientation using a finite-length slender cross section at the clamped root. The accelerometer is mounted on the free end of the instrument tubes inside. Central cluster of instrument tubes is located over 5~7 layers in a row and 2~5 layers in a column downside of 6x8 tube array. During the steady-state condition of stepwise flow increase up to maximum flow rate, acceleration of the 8~10 central cluster instrument tubes among 6x9 tube array were recorded, then the peak components of vibration response spectrum were plotted with reduced velocity. Turning point of the curves were identified to critical velocity (V_{cr}) with the peak frequency variation along the flow increase.

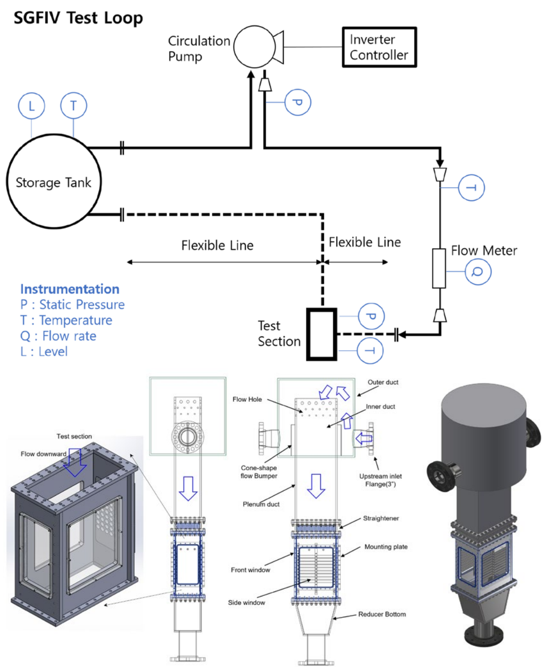
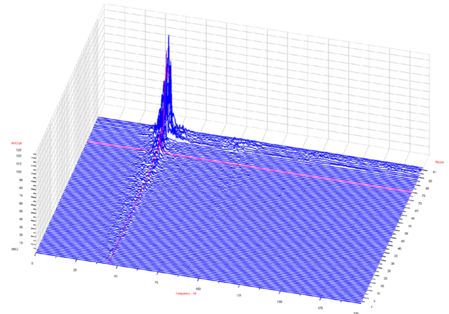


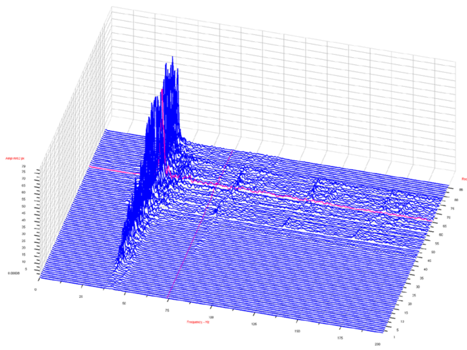
Fig. 1. P&ID drawing of SGFIV test loop and configuration of the test section.

3. Test Results

Fig. 2 and 3 shows representative vibration responses of the tubes within the staggered tube array in two particular preferentially flexible directions (OOP, IP) during the flow sweep test (Fig. 2) and steady state FEI testing(Fig. 3). For the OOP case, tubes become abruptly unstable if the tube vibration reaches to the critical state at around 3.75 in reduced velocity. On the other hands, tube vibration in IP direction reaches to semi-critical state very early at around 2.0 and gradually increase with the reduced velocity. This can be vibration induced by another mechanism, such as vortex shedding. Interesting thing to note worth is that tube vibration in IP direction become stable again after semi-instability at above 4.5 reduced velocity. Re-stabilization of the tube vibration during the FEI test was reported in literature [3], but proper reasoning was not fully understood. Fluidelastic vibration of the given test tube array behaved very differently according to the preferential flexible directions. And semi-critical state or large vibration for IP direction can bound the tube design evaluation due the low value of flow velocity, but the instability to OOP direction looks more fatal to structural integrity aspect because it causes the tube vibration to diverge without re-stabilization.



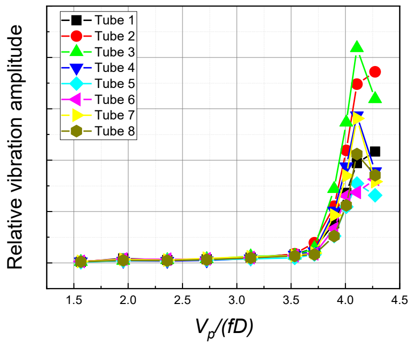
(a) Out-of-plane direction



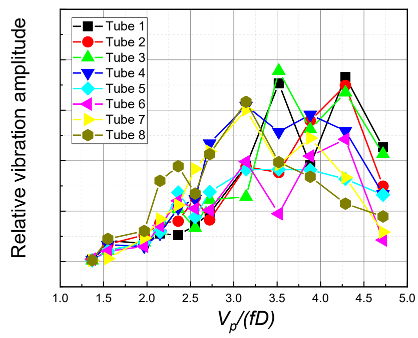
(b) In-plane direction

Fig. 2. Representative vibration responses in two particular preferentially flexible directions during the flow sweep test (z axis indicates the flow increase, the number intentionally scaled)

The OOP instability is more common incident for current steam generator design, but the SG tube failure of San Onofre Nuclear Generating Station(SONGS,US) is known to be IP instability, which occur at very higher flow velocity. New SG design for Korean SMR should be further verified through more experimental and analytical studies.



(a) Out-of-plane direction



(b) In-plane direction

Fig. 3. Peak vibration response in two particular preferentially flexible directions with the reduced velocity over the FEI test program.

4. Conclusion

This experiment discusses the fluidelastic instability of given staggered tube array in preferentially flexible orientation to single phase cross flow. IP instability occur earlier than OOP one, but potential consequence from the OOP instability would be anticipated more fatal. Test data will support to verify SG tubing design and evaluate the design integrity.

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