Added mass and under-water damping of flexible tube in staggered tube array for estimating instability constant

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1. Introduction

Flow-induced vibrations (FIV) of the internal system components in nuclear power plants can cause significant system failure and safety issues. Fluidelastic instability (FEI) is one of the most critical flow-induced vibration 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/developer 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 launched the experimental R&D project named as Flow-induced vibration and Wear testing of steam generator helical tubing. Here in this paper, the added mass and under-water damping ratio of instrument tube in representative type of staggered tube arrays were measured in two independent preferentially flexible directions. This experiment is carried out for preparing input data of integrity evaluation and estimating FEI instability constant.

2. FEI Theory and Experimental setup

When the tubes in bundle vibrate in the cross flow, the vibrations of tubes alter the hydraulic force field near tubes. As the results, the fluid force in turn leads to further displacement of the structure. This back and forth interaction goes on and on. If the energy dissipation mechanism of the tube bundles is not enough to suppress the tube vibration as flow velocity increases, then the amplitude of vibration increases rapidly at a certain flow velocity that is called a critical flow velocity(V_{cr}). The phenomenon of the large vibration is called as fluidelastic instability. The onset of instability is dominantly governed by the following dimensionless variables in single phase flow: the mass damping ratio($2\pi\zeta m/\rho D^2$), the reduced velocity(V_{cr}/fD) and pitch-to-diameter ratio(P/D). It is worth noting that added mass effect may become much larger because of the confining effect of surrounding tubes. For most cases, the Reynolds number in fully turbulent flow (Re >2000) is not expected to play a major role in the instability. The relationship between the parameters can be investigated theoretically or experimentally. Conner suggested an experimental correlation in Equation (1) that is commonly used in this research field nowadays [3].

$$V_{cr}/(fD)= K(2\pi\zeta m/\rho D^2)^a \quad (1)$$

where, instability constant, K, and exponential index, a(≈commonly takes 0.5 for single phase cross flow), are function of the tube array geometry. Damping ratio, ζ, and total mass of tube per unit length, m.

Fundamental natural frequency and damping ratio are essential parameters to evaluate fluidelastic instability. Test tubes for this characterization in air and under still water were firmly mounted on the mounting plate that is installed at the test section. Figure 1 shows cross sectional view of the test bundle modal testing, for characterizing added mass and under-water damping in a submerged tube bundle within the test section. A number of flexible tube can distribute the vibration frequency of target tubes into a group frequency by inter-tube hydrodynamic coupling. Thus, other tubes neighboring instrument tube were fixed in the under-water modal testing. The degree of confinement around instrument tube differ the value of measured damping and added mass.

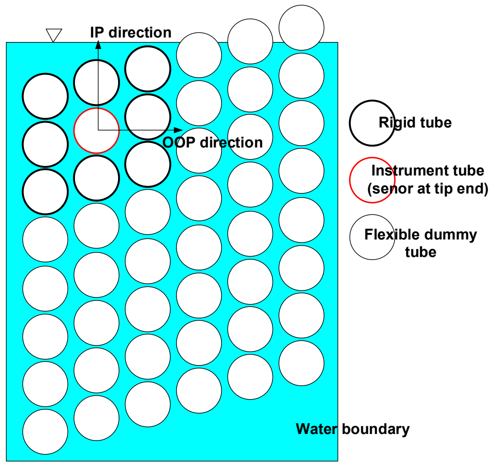
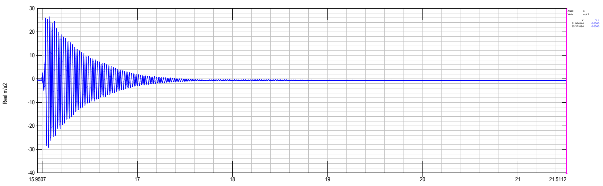


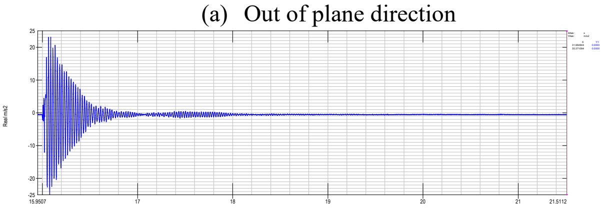
Fig. 1. Cross sectional view of the test bundle modal testing under water for characterizing added mass and under-water damping within the test section.

3. Test Results

Figure 2 shows residual acceleration time histories of instrument tube (senor installed at the tip end) in two preferentially flexible directions (OOP, IP), submerged in the still water. The tube is triggered to the designated orientation by manual plucking with the sharp stick. Instrument tube is surrounded by the 8 rigid tubes among full batch of 6x9 tube arrays. Time response from IP setting with closer inter-tube gap has some beating from the closely located double peak components in the response spectrum (Fig. 3). But, result from OOP setting, on the other hands, appears in the single isolated peak. Figure 3 is the averaged response spectrum from the signal processing of the 3 independent pluck excitations to instrument tube. The fundamental frequency and damping ratio can be estimated from the peak component in the response spectrum by peak picking and half power bandwidth method.



(a) Out of plane direction



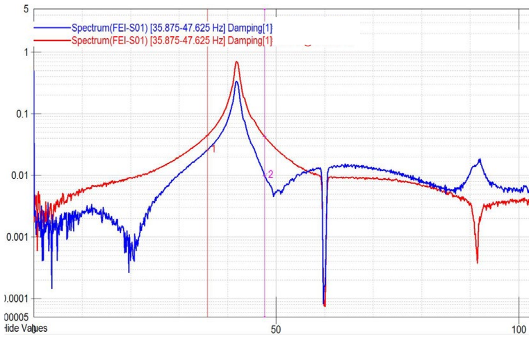
(b) In plane direction

Fig. 2. Response acceleration time histories of instrument tube (accelerometer installed at the tip end) in two preferentially flexible directions (OOP, IP), submerged in the still water and given staggered tube array.

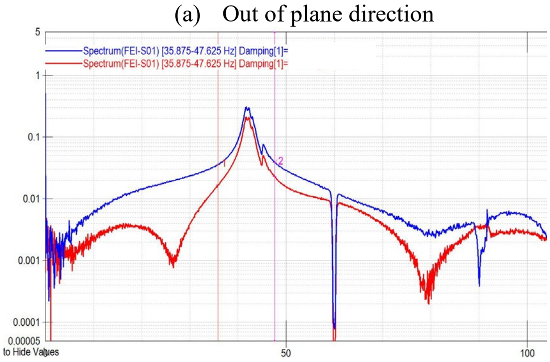
Added mass of instrument target tube within the surrounding tube array can be estimated from the natural frequencies in air and under water as following equation (2). But the measured frequency of a tube surrounded by the fully flexible tubes would be distributed to group frequency of finite range. This can be a problem when one isolated frequency of tube is needed for further analysis. Thus, our resolution is sourrounding to to set to fix.

$$m_{add} = m_t(f_{air}^2/f_{water}^2 - 1) \quad (2)$$

Where m_{add}: added mass, m_t: tube mass, f_{air}: natural frequency of tube in air, and f_{water}: natural frequency of tube under water. Then underwater damping ratio of submerged instrument tube, surrounded by the tube bundle, can be directed estimated from the peak in the response spectrum, as shown in the Figure 3. As easily expected, the damping ratio in IP setting with closer inter-tube gap is higher (1.25%) than that (0.89%) of the OOP setting. This is because the closer inter-tube gap can be act as a squeeze film, described in the literature [3]. Squeeze film damping can be the most important damping mechanism in some application of steam generator tube vibration.



(a) Out of plane direction



(b) In plane direction

Fig. 3. Averaged response spectrum of instrument tube in two preferentially flexible directions (OOP, IP). Tube in IP direction has closer inter-tube gap.

4. Conclusion

This paper discusses the added mass and under water damping of submerged tube bundle for estimating FEI instability constant in two preferentially flexible orientations. Test data will support to verify SG tubing design and evaluate the design integrity. Further numerical study will support the proper reasoning why the frequency and damping of submerged tube bundle in IP direction, with closer inter-tube, is different to OOP one.

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