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Short Note on the Fluidelastic Instability of Steam Generator Tubing

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1. Introduction

Flow-induced vibrations (FIV) of the internal system components, working in coolant flow, in nuclear power reactor is unavoidable, but can cause serious system failure and safety issues in near term or long term perspectives. Fluidelastic instability (FEI) can be the most critical FIV mechanism to steam generator tubing [1], as an catastrophic steam generator failure example of SONGS nuclear power station in US[2]. Here in this paper discusses on some technical aspects on the FEI of steam generator tubing from our experiences, in mostly non-uniform cross flow, to remind the importance of FEI phenomena in the steam generator design evaluation and its licensing guidance.

2. Short note on FEI

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 interactions goes on and on. If the energy dissipation 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. The phenomenon of the large vibration is called as fluidelastic instability. Figure 1 shows the schematic and mathematical overview of the FEI, based on the Qusai-steady model [3]. In short of Figure 1, the FEI is strongly-coupled hydrodynamic and structural instability mechanism, fundamentally induced by the inclined angle of relative flow velocity and time delay between tube motion and fluid dynamic force. We should keep in mind that the fluid force coefficient is function of time and inter-tube relative position, and FEI force can be modelled as linearized fluid forces as shown in Figure 1.

In the simple engineering way, 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/fD) and pitch-to-diameter ratio(P/D). It is worth noting that the 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 [4].

General features of tube vibration during instability are followings [4~7]: Vibration amplitude increase very sharply with the flow velocity, roughly with V^n where n >3.

Mostly, vibration behavior around FEI is not steady in time, but rather beats with infrequent amplitude modulation, increasing and decreasing with respect to a mean value. Tubes without intentionally flexible direction often behave synchronized orbit motions with neighboring tubes. Thus, the usual FEI test setup uses preferentially flexible tube design of slender cross section at the mounting. This can make the tube mostly vibrate in one selected direction.

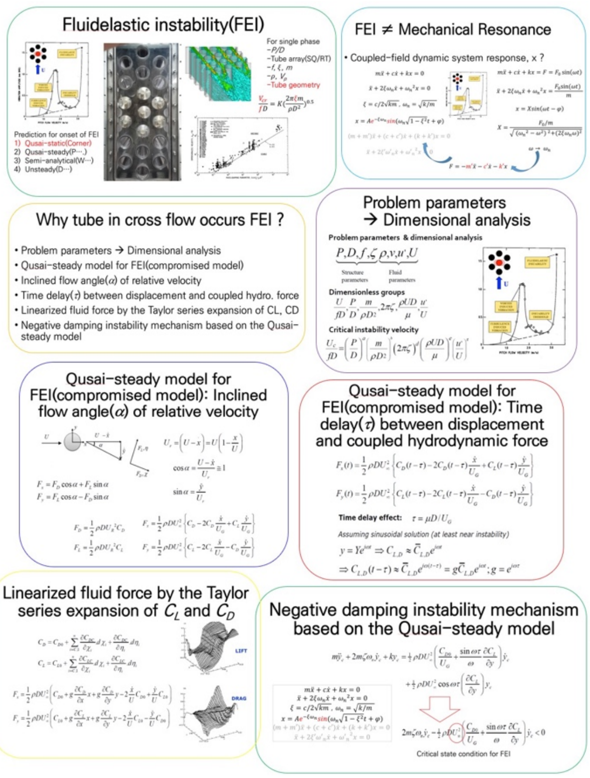

Fig. 1. Schematic and mathematical overview of fluidelastic instability phenomena for tube bundle in cross flow.

Once tube bundle reaches to the instability, frequencies of tubes become synchronizing into one frequency value. This is very important decision parameter to identify the critical velocity in case of smoothly-varied turning point.

Restricting the motion or introducing frequency differences (or multiple frequencies of tubes within one test batch) between one or more surrounding tubes often increase the critical velocity. Slight varied configuration of the array can lead to increase or decrease the critical velocity from this point of view.

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 [5~7].

$$V/fD = K(2\pi\zeta m/\rho D^2)^a \qquad (1)$$

where, instability constant, K, and exponential index, a, are function of the tube array geometry and other relevant parameters. In the test setup for straight and curved tube bundle, it was tried to search for f(natural frequency), under water and V_{cr}. Then, It will be estimated for K using Conner's equation based on the parameters above. Figure 2 shows a usual data reduction process in common FEI test.

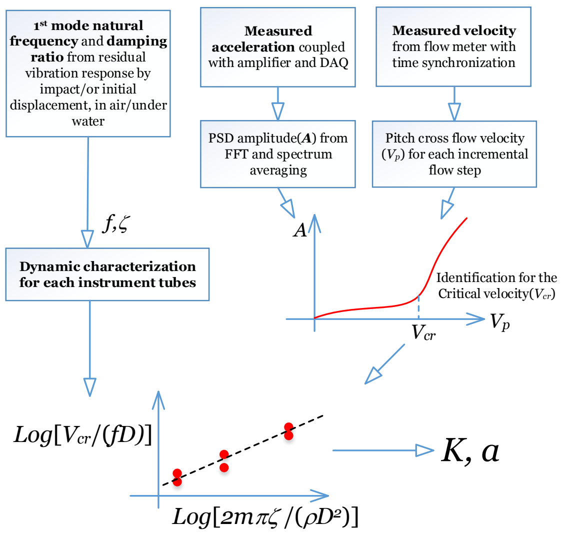

Figure 2 Common Data Reduction Process of FEI test

Most cases in common FEI testing for searching critical velocity (V_{cr}), vibration orientation of the tubes is restricted to the certain direction of stream-wise or normal to the flow direction. Usual V_{cr} for stream-wise flow direction is a way higher than that of normal-to-flow direction.

Furthermore, from our experience, the amplitude of the tube vibration in the stream-wise flow direction shows very different trend along the flow increase to the other case of vibration direction. That includes some early increase of vibration at the low flow velocity zone and some re-stabilization trends of tube vibration over the higher flow velocity zone. These phenomena are not fully understood yet. Recent our measurement and signal analysis, not published yet, shows some evidence that those are originated from the inherent flow periodicities, varying with the flow velocity, within the staggered test arrays. Further data collection to proof our hypothetical reasoning is needed in the near future.

Lastly, ASME design guideline [4] is a potential option to investigate this problem, but the guideline is too general and provides too wide range (from water to gas mixture) of mass-damping parameter in FEI stability diagram. Thus, further experimental test to focus on the specific operational condition would be needed to design new types of steam generator and their specific operational condition.

3. Conclusions

Here in this paper discussed on some important technical aspects on the FEI of steam generator tubing in mostly non-uniform cross flow, to remind the importance of FEI phenomena in the steam generator design evaluation and its licensing guidance. FEI of SG tubing mostly depends on the two main parameters, i.e, reduced velocity and mass-damping parameter for given tube array with certain P/D. And the advanced guideline should be revised and prepared further for design validation of new type of steam generator, to consider specific operational condition and steam generator design, instead of applying current guideline with broad ranges of mass-damping parameter.

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