CFD Simulation of Acoustic-Induced Vibration in Main Steam Line of APR1400

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1. Introduction

In recently, many boiling water reactors (BWRs) implement extended power uprate (EPU) to increase economic benefits. After EPU, Quad Cities power plant has been experienced damage of steam dryers due to acoustic-induced vibration. Acoustic resonance is produced by the interaction between the sound field and an unstable shear layer when the dry steam flows across the closed branch pipes such as safety relief valve(SRV). The unsteady vortices are separated at the leading edge of branch pipe and generated fluctuating pressure wave. After this experience, US-NRC issued that the licensee for new type of reactor should perform a vibration assessment program for an adverse flow effect in the main steam line in accordance with regulatory guideline 1.20 revision 3.

In Korea, KHNP CRI implements comprehensive vibration program for steam generator of APR1400 and evaluates acoustic-induced vibration in main steam line using a commercial CFD code, ANSYS CFX 13.0. This paper deals with benchmark analysis to obtain applicability and reliability of commercial code for prediction of acoustic resonance phenomenon in case of single branch pipe test. Based on the benchmark analysis, analysis of main steam line in APR1400 plant is performed. In case of APR1400, five main steam safety valves are installed in the main steam line. Finally, this paper shows a prediction result of acoustic-induced vibration characteristic in main steam system of APR1400.

2. CFD Models and Boundary condition

2.1 CFD Models

To predict flow-induced noise or resonance, an highly degree of turbulence model is necessary. CFX code provides Detached-Eddy Simulation (DES) model that can be suitable for prediction of a detail turbulent flow structures and spectral distribution. In this study, DES model is used for the transient simulation in the benchmark analysis and the real plant analysis.

In the benchmark analysis, air ideal gas was applied for simulating the compressibility of working fluid in the system. In case of APR1400 analysis, real steam properties with IAPWS-IF97 look-up table are used to simulate real steam properties in the secondary system of plant.

Based on the previous experiments, a correlation of acoustic resonance frequency is suggested as follow.

$$f_n = \frac{a(2n-1)}{4(L+L_e)} \quad n = 1,2,3 \ldots \qquad (1)$$

Where, a is speed of sound, n is mode order, L is length of branch pipe, L_e is the end correction (0.425d), d is diameter of branch pipe.

CFD results will be compared with a result calculated by this correlation.

2.2 Boundary Conditions

As presented in Table I, single branch experimental conditions are applied for CFD boundary conditions. In case of APR1400, conditions of secondary system are applied for CFD boundary at 100% full power operation .

Table I: Boundary Condition

	Single branch case	APR1400 case
Inlet flow Velocity	77m/s	40m/s, 60m/s
Reference pressure	Atmospheric pressure	992 psi
Reference temp.	Room temperature	550
Wall condition	No slip, adiabatic	

3. Analysis Results and Discussions

3.1 Benchmark Analysis

Based on Eq. (1), acoustic resonance frequency in benchmark case is evaluated about 1447Hz. As shown in Fig. 2(Left), when the flow velocity reached at 77m/s, the fluctuating pressure is periodically amplified. To analyze the frequency spectrum of fluctuating pressure, FFT (Fast Fourier Transform) analysis is performed as shown in Fig. 2(right). The abscissa is normalized by the acoustic resonance frequency calculated by Eq. (1). A significant resonance peak can be observed at Fig. 2(Right). This means that fluctuating pressure reached at resonance conditions. In conclusion, results of CFX code show a good prediction for acoustic-induced vibration phenomenon.

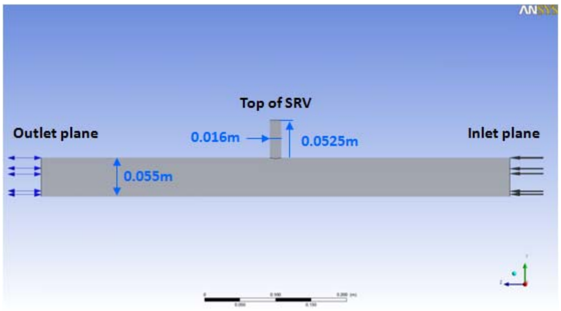

Fig. 1.Dimension of test section for benchmark analysis

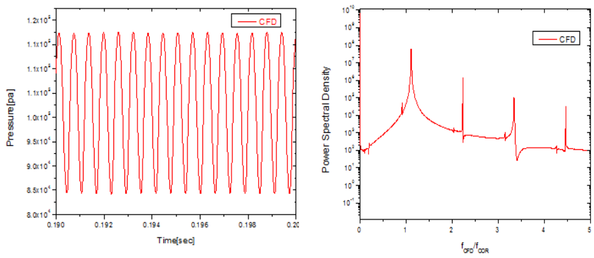

Fig. 2. Fluctuating pressure and power spectral density of acoustic-resonance wave

3.2 APR1400 Analysis

As shown in Fig. 3, five main steam safety valves are modeled in APR1400 analysis. Ideal acoustic resonance frequency can be calculated by Eq. (1) and is about 165 Hz at first resonance mode (n=1).

Highly periodical pressure is observed at MSSV #2 as shown in Fig. 4(Left). A various frequency and amplitude are predicted at all MSSVs. As presented in Fig. 4(Right), power spectral density (PSD) distribution is suggested to evaluate frequency spectrum at each MSSV using FFT analysis. At around 180 Hz, all MSSVs have an identical resonance peak in PSD distribution. In the second resonance mode (n=2), MSSVs have a smaller resonance peak. This result shows that certain acoustic-induced vibration is generated at each MSSV under full power condition of APR1400. Although MSSVs have resonance peaks, there are no significant difference between the various noise peaks and acoustic resonance peak in each frequency domain. It means that full power condition of APR1400 does not seem to be a fully developed resonance condition. To find a fully resonance condition on the main steam system of APR1400, additional analysis is performed under 60m/s of inlet steam velocity condition.

As presented in Fig. 5, PSD distributions of all MSSVs have identical resonance peaks in each resonance mode and resonance peaks are clearly distinguishable compared with noise peaks. Nevertheless, structural analysis should be conducted to evaluate the structural safety based on the results of full power condition in APR1400. This calculation results will be used as a hydraulic forcing function for a structural analysis.

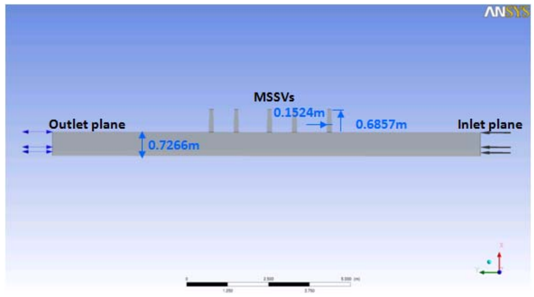

Fig. 3.Dimension of main steam line for APR1400

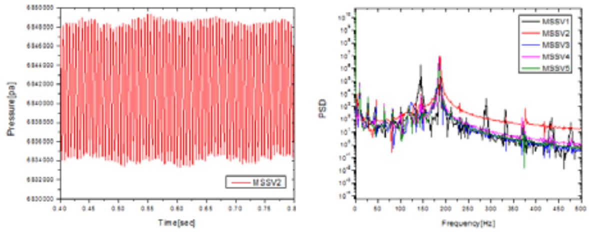

Fig. 4. Fluctuating pressure and power spectral density of acoustic-resonance wave at full power condition(40m/s)

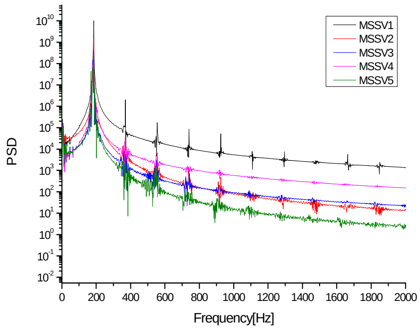

Fig. 5. Power spectral density of acoustic-resonance wave at 60m/s

4. Conclusion

To evaluate the acoustic-induced vibration on the main steam line in APR1400, a series of CFD analysis is performed. The results of benchmark analysis for single branch experiment provided a good prediction and code reliability. Based on this experience, hydraulic forcing function generated by acoustic resonance is calculated under a full power condition of APR1400. Structural analysis will be performed to evaluate a structural integrity although the result shows that acoustic-induced vibration does not seem to be a fully developed resonance condition.

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