MODAL CHARACTERISTICS OF THE FIV TEST LOOP

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ABSTRACT

The high performance fuel development in KAERI has been developing the spacer grids being used as a core structural component of the nuclear fuel and also performing basic study on their mechanical performance. The vibration and other mechanical / structural characteristics of newly developed nuclear fuel should be evaluated through out-of-pile flow test before in-reactor performance verification. From this reason, KEARI has developed the new test loop for the small-size fuel bundle. The test bundle of 5x5 partial PWR fuel assembly will be tested for the study on the flow-induced vibration and the coolant hydraulics. As a preliminary step for the FIV test, the modal characteristics of the FIV test loop was investigated by the two methods; the finite element (FE) analysis using commercial FE code, ABAQUS, and the modal test with an impact hammer and accelerometers in air and under water filled. The FE analysis results were compared with those of the experimental modal test for the result verification. Five modal modes for the main pipeline for the test loop were identified in the frequency range of interest, below 60 Hz. From the vibration spectrum measured in the flow sweep test for the loop, the effect of the flow on the loop vibration and its directional dependent properties were presented.

Keywords: Flow-Induced Vibration (FIV), FIV Test Loop, Modal Parameters, Pressurized Water Reactor (PWR), Fuel Assembly (FA), Spacer Grid (SG)

1. INTRODUCTION

The PWR nuclear fuel bundle is located at reactor in-core and subjected to axial coolant flow, 5~8 m/s. The vibration due to the axial flow can induce a relative motion between the cylindrical fuel rod and the supporting point (or area) of the spacer grid, even a small amplitude vibration results in impacting, and hence, fretting and wear might cause damage on the surface of the nuclear fuel rod with serious consequence. The problem arises mainly from close spacing between the fuel rods and spacer grids on adjacent counterpart or intermediate imperfect supports. Another important factor in axial flow-induced vibration is that fuel systems are inherently
very flexible because of material make-up, manner of support or contact condition, so that they are prone not to larger-amplitude vibration (Paidoussis, 2004). Thus, from the design stage, it is important to consider the vibration behavior of the fuel components and spacers so that the fuel can be used without any damage from mechanical causes for the fuel lifetime (3~5 years).

From the previous studies for the vibration behavior of the fuel rod with spacer grids, the vibration characteristics can be changed according to the design of the spacer grid which supports the fuel rod, and those are reported by Kang et al.(1998) for the fuel rod with several types of spacer grids. It is believed that the new design for better spacer grids and the support condition can improve the fuel performance as a nuclear fuel and the failure probability might be reduced.

The vibration and other mechanical / structural characteristics of newly developed nuclear fuel should be evaluated through out-of-pile flow test before in-reactor performance verification. KEARI has been planning the flow-induced vibration (FIV) test using the small-size trial nuclear fuel for the same reason. The FIV test is also one of the screening tests such as an impact, a buckling, a fretting wear and supporting performance one, to determine final spacer grids type for the commercialization. This study for the test bundle is differentiated with previous researches (Kang et al, 2003, Choi et al, 2004) which only performed for vibration characteristics of a unit fuel rod with spring/dimple of the spacer grids in that the coupled effect due to coolant flow on the structural characteristics of fuel rod and spacers is considered.

The FIV test loop was designed and constructed by the pure domestic technology with reference to the hydraulic test loop (VISTA) of Westinghouse Co.(Kang et al., 2002) The test conditions will setup to severer than the reference loop, such as the pressure of 10 bars and the maximum flow velocity of 12 m/s. The coolant flows through transparent test section inside in axial direction. The reservoir being able to control the coolant temperature by inside heating coil, the centrifugal pump with an inverter and two flow meters are connected to the main pipeline. A Pump and reservoir capacity was determined by considering a specification of the fuel rod being used the previous study and the test condition to be planed. The test bundle to be used at the FIV test is a small-scale trial fuel of half in length and one tenth in cross sectional dimension to the commercial fuel. It is consists of 23 dummy fuel rod included with 2 accelerometer tube, 2 guide tube, and 5 spacer grids. A schematic layout of the test loop and test bundle was shown in Figure 1.

With a construction of the test facility completed, as a preliminary step for the FIV test using the test bundle, the modal test and finite element analysis to identify modal properties of the loop were conducted for the initial loop design and its supports (Lee et al, 2004a). The natural frequency and lower mode shapes of the loop are used for estimating the support performance of the support structures and rod-clamping tools. The loop design and its supports were modified to minimize the loop vibration by adding restraints to the weakly supported region, changing the flow path for diminishing the vortex and turbulence above the test section, and so on.

In this paper, finite element (FE) analysis using commercial code, ABAQUS, and modal testing with impact excitation technique for the modified test loop was performed to find out the modal characteristics of the loop in air and under water filled. The modal parameters of the loop will be used for the analysis the FIV test results as a loop characteristic data and for developing the modal model for the loop dynamics. The FE analysis results were verified by comparing with those of the modal test. Additionally, as a basic study on the pipe conveying fluid problem, the effect of the flow on the modal characteristics of the loop is also discussed from the analysis of the loop vibration response measured from the flow sweep test.

2. METHOD

As previously mentioned, the original loop after the performance evaluation by the pre-analysis and the test undergoes some design changes such as smoothing elbow shape above the test section, adding supports at the high vibration amplitude region near up and downstream of the restoring pipeline for the purpose of improving support performance and reducing vibration due the flow in light of the analysis results. For the free vibration and flow-induced response characteristics of the modified loop, the following finite element analysis, the modal testing and the flow sweep test were conducted as below.

2.1 FINITE ELEMENT ANALYSIS
For the loop modeling and the numerical modal analysis, the commercial FE code, ABAQUS, was used. The 3 dimensional beam element (B31) was used for the pipeline, the support structure, and the test section according to respective sectional makeup. Applying beam orientation to the FE model should be careful not to beam normal to direct their tangential orientation. The specification of the SUS pipes referred to the KS and ASTM pipe standards.

The lumped mass element (MASS) was employed for the valves, flanges and clamping protector for the test section as a real mass (kg), not a weight (kgf). The restraint was modeled by a linear connector with axial spring whose constant is $4.6 \times 10^6$ N/m for vertical support and $1.6 \times 10^6$ N/m horizontal one. The spring constant for the restraint was determined by the additional numerical simulation with real-size FE model because no available literatures can be referred. The flexible joint and bellows near the up and downstream of the test section was modeled by weakening (decreased over 50% in both parameters) the equivalent pipe model in thickness and stiffness according to the engineering experience, but the modeling of the vibration properties for the flexible bellows in the pipeline system is technically challenging.

The pump and reservoir on the whole loop model are ignored because of the far-away from the main loop. The lanczos method was employed to extract analytical modal parameters of the loop. The materials of the pipeline and the support structure are a stainless steel, and a acrylic for the test section, their elastic modulus and Poisson’s ratios used in the FE analysis are 210 Gpa, 0.3 and 30 Gpa, 0.33, respectively. The density of each material is 7800 kg/m$^3$ for the steel, 1300 kg/m$^3$ for the acrylic. Figure 2 shows the finite element model with the boundary and interaction conditions.

2.2 The MODAL TESTING / ANALYSIS

Purpose of the modal testing and analysis was to get modal parameters of the system experimentally and compare with those of the FE analysis. If the modal parameters of the system were identified by conducting either the test or the FE analysis, building a modal model of the system are based on this modal parameter of the system, then, predicting the response of the system due to arbitrary set of inputs is capable.

Impact excitation technique was employed to extract the modal frequency, damping, and shape of the first five flexural modes of the main loop. The impact excitation is relatively easy and quick to implement using modal hammer (PCB 086D20) weighting approximately 1.1 kg with load cell. A soft rubber tip was attached on the free surface of the load cell.

Three or five impulses were averaged at one impact position at the bottom flange of the test section in order to obtain the frequency response functions (FRFs). The FRFs have been measured at 12 response points over the main pipeline. Both excitation force and measured responses have been in the frontal direction (the east direction of the test building) on the test section. The response and excitation points have been determined by the FE analysis results of the loop; this allows for detection of mode shapes with up to 5 bending modes for the main pipeline.

The data acquisition & control system (VXI HP 7500), signal conditioning amplifier (B&K NEXUS), and breakout box was used for acquiring and processing data with the following parameters; maximum frequency of interest 100Hz; frequency resolution 0.15 Hz; 5 averages; exponential windows with an impulsive reference for the excitation force for both empty and water-filled loop; The experimental modal analysis was performed by the software MTS/IDEAS PRO and MTS/Reporter. SDOF modal parameter estimation technique was used for estimating modal properties of the loop. SDOF technique assumes that each of the measurements resembles a single degree of freedom system near the frequency that user select. SDOF modal parameter estimation calculates modal coefficients and parameter in least square sense.

2.3 THE FLOW TEST

The flow sweep test for the open loop was performed in two reasons; the one was to investigate the forced vibration characteristics of the loop due to random flow excitation. The other was to identify modal property variation according to the flow. Additionally, the test evaluates the loop performance in the sense of vibration and hydraulic aspects before the FIV test using the test bundle.

Over the steady state flow condition with incremental sweep using inverter-controlled pump rotational speed
change, real time acceleration of the loop and pressure fluctuation inside the test section were measured. The test flow ranges from 1000 to 3000 l/m, which translated to approximate calculated velocities of 4.0 to 10.5 m/s and Reynolds number of 3.4 x 10^5 to 8.6 x 10^5 inside the test section under the temperature range of 40 °C. The test pressure was increased up to 8 bar at the maximum test condition.

For the flow test, HP/VXI front end as a data acquisition device and MTS/IDEAS-PRO as the test data analysis software were used for data processing and analysis. Measurement locations for the vibration response spectrum due to the internal flow was middle of the test section, bottom flange above supplying pipeline under the test section, and top of the test section.

3. RESULT AND DISCUSSION

3.1 LOOP MODAL PROPERTIES

The fundamental natural frequency of the loop based on the test results is 26.8 Hz for the loop in air and 24.2 Hz for the other case under water, after that second to fifth mode are found within the frequency range of 60Hz. As expected, the natural frequencies of the water filled loop are less than about 10% on average compared to those of the empty one. Damping coefficients are a bit larger for the water-filled loop, except for 5th mode. This difference is originated from the still coolant inside the loop due to the added mass effect. Table 1 shows natural frequencies and damping of the loop both from the test and the FEA. The experimental natural frequencies are lower than those of the FE analysis. For the fundamental natural frequency, the experiment shows 8.9% lower value against the FE analysis one, 29.2 Hz. The discrepancies in natural frequencies of the two methods are mainly due to a modeling error of the flexible joint and restraints. Modal damping from the FE analysis is not included in here because the FE model for the loop has not any specific damping model owing to the difficulties in the damping calculation for the pipe element and its connection.

The modified loop shows a bit high (6.9% increase in the fundamental natural frequency) natural frequencies compared with those of the old one, except the third and fifth mode, because the boundary conditions changed to more conservative due to the added restraints.

The measured frequency response functions (FRFs) is shown in Figure 3 with both the amplitude and the phase change and the real and the imaginary part plot for the loop. Frequency response function (FRFs) are a function of the characteristics of the system, and are independent of the input type. Linearity, time invariance, observability and reciprocity are assumed when calculating FRFs. The peaks in the amplitude portion of the plot correspond to the natural frequencies of the loop.

Table 1 Modal properties of the loop (Test results in air and under water filled and FE analysis results)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Test in air</th>
<th>Test under water filled</th>
<th>FEA Modal Frequency(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency(Hz)</td>
<td>Damping(%)</td>
<td>Frequency(Hz)</td>
</tr>
<tr>
<td>1</td>
<td>26.8</td>
<td>1.6</td>
<td>24.2</td>
</tr>
<tr>
<td>2</td>
<td>37.0</td>
<td>1.7</td>
<td>34.8</td>
</tr>
<tr>
<td>3</td>
<td>47.6</td>
<td>1.0</td>
<td>46.2</td>
</tr>
<tr>
<td>4</td>
<td>49.9</td>
<td>1.0</td>
<td>49.0</td>
</tr>
<tr>
<td>5</td>
<td>60.0</td>
<td>1.2</td>
<td>58.2</td>
</tr>
</tbody>
</table>

The mode shapes corresponding to the natural frequencies are the bending vibration modes of the pipe arrangement. Figure 4 presents comparison of mode shapes for the loop from the test and the FE analysis. Though two mode shapes have large difference at some region of the loop, overall trends of the vibration pattern are similar to each other. The discrepancy in mode shape of the two methods around upstream region of the restoring pipeline is assured that the boundary conditions for that region should be replaced to the less conservative boundary.
conditions than the current one. The fundamental mode shape for both test cases and FE analysis was the first bending mode (half-sine in the axial direction) of the simply supported beam for the acrylic test section of which stiffness is less than the other SUS pipe components. The second mode one has a shape like beam second bending mode (a complete sine in the axial direction) with dominant deflection near lower stream of the test section. The higher mode of the loop, the more developed bending shape of the test section, but vibration amplitude over the restoring or supplying pipeline nearly disappeared. This is because the flexible bellows located at the right before and after the test section might made discontinuity in experimental mode shape of the loop. But, in FE analysis mode shape, vibration modes have a smooth pattern because of the analytical manner. Thus, more realistic modeling for the bellows and restraint is needed.

From the comparison of the FEA result with the experimental one in natural frequency and mode shape, FE model for the modified loop is quite reasonable.

3.2 THE FLOW-INDUCED LOOP VIBRATION

Figure 5 shows a comparison between a typical vibration spectrum at the flow velocity of 7.55 m/s and FRF at the same measurement location. On the frequency range of interest, below 100Hz, a dominant periodic component in the spectrum is corresponding to the fundamental natural frequency of the loop, 25Hz. The second dominant component coincides with the third eigenfrequency of the loop, 47Hz. From the general observation of the previous study (Lee et al., 2004b) for the forced vibration due to the flow, the loop shows a complex vibration behavior according to the random flow excitation in broadband sense and dominant periodic components in the loop vibration spectrum appear peaks at the eigenfrequency of the loop. For the certain frequency range, the loop responds to the flow periodic components near the eigenfrequencies of the loop like a band pass filter. The dominant components in the vibration spectrum correspond to those of the flow periodic due to the vibration sources such as pressure fluctuation, acoustic resonance, harmonic with pump blade passing, and vortex shedding, etc. And the loop affected mainly by the periodic components corresponding to the pressure fluctuation in the high frequency vibration region of the nuclear fuel of 1.5 kHz to 3 kHz.

From the FIV test viewpoint, since the fundamental natural frequency of the test loop is near the third natural frequency of the test bundle, there is a need of great care that the pure response of the fuel from the measurement for the bundle's FIV will be differentiated with the eigenfrequency of the loop near that frequency and the loop dynamics doesn’t affect or distort the vibration characteristics of the test bundle over the frequency range of interest.

The amplitude of the periodic components corresponding to the second and fourth eigenmodes of the loop are much less than those corresponding to the first and third eigenmodes because the measurement location is a nodal point in the 2nd and 4th mode shape of the loop. The periodic components in the vibration spectrum corresponds directly to the loop eigenfrequencies within frequency range of interest, though there is a little frequency difference according to the flow. The vibration amplitude for each dominant periodic component in the spectrum according to the flow depends on the mode shape of the loop like above.

Though there are some differences according to the flow condition, the vibration amplitude is varied with the measurement location. The vibration amplitude in spectrum measured at the bottom of the test section is much lower than the middle of the test section which shows maximum vibration amplitude as expected. However, at the frequency of the flow periodicities such as the pump blade passing frequency, the vibration amplitude of the bottom region of the test section is similar or even larger than that of the middle of the test section. This is because the flow resistance is much larger at the measurement position located in the bent region.

3.3 THE FLOW EFFECT ON THE LOOP MODAL

Figure 6 presents normalized flow-induced vibration spectrums of the loop measured at the middle of the test section for the both frontal and side directions according to the flow velocity of 4.2 m/s to 10.4 m/s. The responses of the loop for the two directions show different spectral patterns at each of periodic components according to the flow. The side directional vibration is more complex than those of the front direction. The periodicities in frontal vibration spectrum appeared a constant nature at the same frequency even if the flow changed. This might show the loop vibration has a directional dependent nature. While frontal directional vibration is exactly corresponding to
the eigen-frequency of the loop, but side directional one of which measurement direction is parallel to the flow path has a disperse and random nature in the spectrum with the flow variation.

As flow velocity increased, the periodic components corresponding to the fundamental natural frequency of the loop slightly decreased in both case, but negligibly small. And the side directional behavior is more sensitive in varying trend with the flow. This is because the loop has a directional dependency on both the flow and the flow path. This means the flow excitation has a more sensitive effect on the modal property for the side direction of the loop than that for the frontal direction.

4. CONCLUSIONS

To estimate modal properties of the modified FIV test loop, the FE analysis, the experimental modal testing and the flow sweep test were conducted. Fundamental natural frequency of the modified FIV test loop is 26.8 Hz in air, 24.2 Hz under water condition with the discrepancy 8.2% and 17% respectively to the FE results and 6.5% increased from the initial design, its corresponding mode shape is a local bending mode (beam 1st bending shape) of the test section, slightly differed from the initial design of the loop. FE analysis result was reasonable in both frequency and mode shape but the mode shapes shows a big difference at some region of the loop, hence it is necessary to change the support boundary conditions and bellows modeling more realistic to match the two methods.

From the general observation of the vibration spectrum of the loop due to the internal flow, dominant periodic component in the spectrum are corresponding to the eigenfrequency of the loop and the vibration amplitude at certain frequency in the spectrum depends on the mode shape of the loop according to the flow. The loop vibration has a directional dependency on both the flow and the flow path. This means the flow excitation has a more sensitive effect on the loop vibration for the certain direction.

Finally, the modal properties at some eigenfrequencies show a slight variation according to the flow and the vibration direction, but negligibly small. To identify quantitatively how the flow affect on the modal of the loop, what mechanism of the modal property variation of the loop is, the further study is needed.

ACKNOWLEDGEMENT

The authors express their appreciation to the Ministry of Science and Technology of Korea for its financial support.

REFERENCES

Fig. 1 Schematic layout of the FIV test facility and test bundle

Fig. 2 Finite element model

Photo. 1 FIV Test Loop
Fig. 3 Measured frequency response functions of the loop; (a) amplitude and phase change, (b) real and imaginary, for the response near the test section.
Fig. 4 Vibration mode shape of the main pipeline; (a) the first mode for test, (b) the first mode for FEA, (c) the second mode for the test, (d) the second mode for the FEA, (e) the third mode for the test, (f) the third mode for the FEA, (g) the fourth mode for the test, (h) the fourth mode for the FEA, (i) the fifth mode for the test, (j) the fifth mode for the FEA
Fig. 5 Typical response spectrums at same response location; (a) response spectrum with respect to the flow at flow velocity 7.55 m/s, (b) frequency response spectrum from the modal test., Pos. #1 : middle of the test section, Pos. #2 : bottom of the test section.

Fig. 6 Normalized flow-induced vibration response spectrum of the loop according to the flow; (a) side direction of the loop, (b) frontal direction of the loop, V 4.2 means flow velocity of 4.2 m/s inside the test section.