Bending Wave Propagation Analysis Induced by Metal Ball Impacts on Reactor Pressure Boundary Structure

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ABSTRACT

Recently, a model-based prognostic approach is becoming one of noticeable techniques to predict the fault behaviors of mechanical components in nuclear power plant. Lamb's general solution for an arbitrary impact force function and Hertz impact theory have been used to identify the bending wave characteristics impacted by a metallic loose part in reactor pressure boundary components. However. these approaches can hardly provide an information on accurate acceleration response for identifying the impact source. In this study, the impact response characteristics such as maximum acceleration amplitude and primary frequency of the impact response signal by a simulated loose part (metal ball) are analyzed using finite element analysis (FEA) and the FEA-based model is verified by experimental results. It is expected that the developed FEA-based model can be utilized in model-based prognostics for localization and estimation of mass of loose part in nuclear power plants.

1. INTRODUCTION

Loose part such as nuts, bolts, pins, sections of tubing, and hand tools used in maintenance and found in the primary coolant systems of pressurized water reactors, could damage steam generator tubes, reactor internal parts, reactor coolant pumps, and so on. Two major goals should be considered in monitoring loose part in nuclear vessels: (1) localization, which is the estimation of where the loose part is and (2) mass estimation of the loose part. Some successful approaches for localization have been realized, such as the hyperbola intersection method, circle intersection method, triangular intersection method, and so on (Kim et al., 2002, Olma, 1985, Ziola, 1991). However, an additional study for mass estimation is still required. In general, Lamb's general solution for an arbitrary impact force function and Hertz impact theory have been used to identify the bending wave characteristics impacted by a metallic loose part in reactor pressure boundary components (Mayo, 1994). However. the approach can hardly provide an information on accurate acceleration response for identifying the impact source. Also, the experimental method is a time-consuming and expensive process and lacks scientific insight. Owing to the increase in computing power, the finite element analysis (FEA) method has recently become an available option to simulate impact-responses of nuclear structures. Therefore, artificial intelligence (AI) technology and FEA-base model can be applied to estimate the loose part's characteristics such as mass, velocity, shape, impact location and so on.

The objective of this study is to develop a FEA-based model that can be used to simulate the impact behavior between a metallic loose part and dispersive plate structures such as the reactor and steam generator vessels. An impact wave propagation test and simulation by FEA for a plate was conducted, and the validity of the FEA-base model was proven. Also, a novel concept was proposed to estimate the mass, velocity, shape and impact location of a metallic loose part.

2. IMPACT WAVE PROPAGATION TEST

The impact wave propagation tests for a curved plate, a half scale steam generator (SG) of Korean Standard Nuclear Power Plant, were conducted to measure the mechanical impact behavior in the structure. A primary head of half scale SG was presented in Figure 1(a) , and that was made of 304 stainless steel. A steel ball with a mass of 46.0 g and a velocity of 1.0 m/s impacted the curved plate in normal direction of that as shown in Figure 1(b), and then the acceleration signals were stored at a sampling rate of 200 kHz with ten accelerometers attached at 0.05 ~ 0.32 m away from the impact point.

3. IMPACT WAVE PROPAGATION SIMULATION

The impact wave propagation behavior in the curved plate structures was estimated through elastic FEA, and then the results were compared with the corresponding experimental one. The FEA was performed with an implicit solver in ABAQUS Version 6.14 package. Figure 2 shows a typical finite element mesh of the analysis object. The mesh was constructed with axisymmetric 3 or 4 node linear elements and 8 node quadratic elements. The acceleration data were stored at a sampling rate of 1 MHz.

Figure 3 shows the calculated acceleration signal and measured acceleration at 0.3 m away from the impact point, filtered with a low-pass filter with a cut-off frequency of 20 kHz. The acceleration signal from the FEA shows a good agreement with one from test. The calculated amplitude showed a good agreement with the test amplitude within 3 % difference. Time-frequency analysis results using the Wigner-Ville distribution for acceleration signals are shown in Figure 4. The center frequencies obtained by test and FEA were 11,268 Hz and 10,597 Hz, respectively, and showed 6 % difference.

A good correlation in the amplitude and the frequency of the bending waves propagating in the curved plate were obtained between the measurements and predictions, validating the FEA model develop in this study. Thus, it is thought that FEA technique can be used for mass estimation of the loose-parts in a nuclear power plant.

4. NOVEL REASONING METHOD OF IMPACT PARAMETER

Transient elastic wave caused by a loose part impact on the inner wall of the coolant system is detected by accelerometers. The wave is characterized with the mass, velocity and shape of a loose part, and the distance between the impact location and the sensor location. Therefore, each unique mass, velocity, shape and impact point, which are potential impact parameters, have a unique vector (Liska et al., 2016). Conversely, a measured vector uniquely determines the value of impact parameters. Therefore, the corresponding unique vector set for a sufficiently rich set of impact parameters can be calculated by FEA-based model. Ultimately, values of impact parameter can be determined from measured impact signals and a unique vector set for a set of impact parameter using AI. Figure 5 shows the new reasoning method for impact parameter prediction.

(a) Test facility (b) Schematic diagram of impact test

Figure 1. Experimental set-up for impact test.

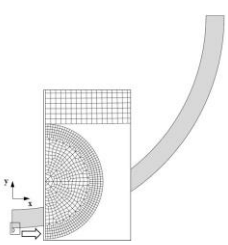


Figure 2. FEA model.

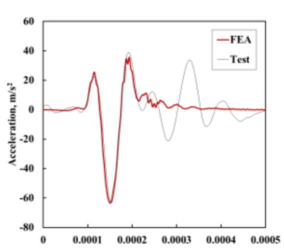
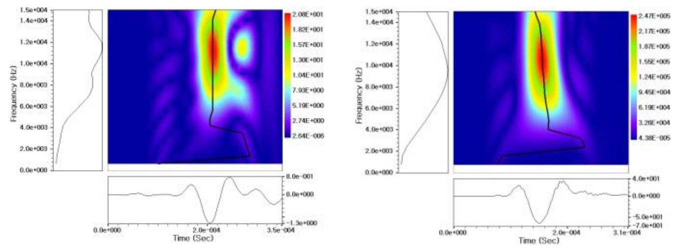


Figure 3. Acceleration response signals.



(a) Test (b) FEA

Figure 4. Wigner-Ville distribution of acceleration response signals.

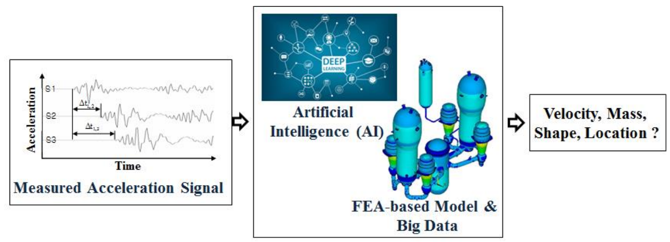


Figure 5. Novel reasoning concept of impact parameter.

5. CONCLUSION

In this study, FEA-based model was developed to simulate the impact behavior in the curved plate structure of nuclear power plant, and the model was verified by experimental results. In addition, a new reasoning method for impact parameter prediction was proposed. It is expected that the developed method can be utilized in model-based prognostics for estimation of impact parameters such mass, velocity, shape and impact point of loose part in nuclear power plants.

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