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ANN based localization of metal ball impacts on reactor pressure boundary structure

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Abstract

Recently, AI and machine learning technique influences all the areas in industry, academia, and even art, and makes noticeable changes in their future map. The analysis and prediction on this phenomenon is still undergoing. Likewise, these technology also are affecting the area of model based prognostic approaches that 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 the 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 are achieved by experiments and FEA-based analysis. And an artificial neural network is built up to realize an automated localization of metallic loose parts impacting on reactor pressure boundary structure.

1. Introduction

Various types of 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. Some of the loose parts are given in Figure 1.

(a) Pins (b) Nuts (c) Thermal Sleeves

Figure 1. Examples of the loose parts

Monitoring these loose parts in nuclear vessels should include localization and mass estimation of the loose part, where the localization means finding out the location of the loose part.

Several successful approaches for localization include 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 above-mentioned approaches can hardly provide useful information on accurate acceleration response for identifying the impact source. On the other hand, experimental methods are time consuming and expensive processes. These approach gives no scientific insight.

In this study, experimental study is done first to get some actual response from the physical test bed. An FEA based analysis and modeling are achieved by using the experimental data to verify FEA model. And all the data from experimental and FEA based simulation are used to train an artificial neural network to establish an automated estimator for identifying the characteristics of the loose parts. Even if this study is dealing with the localization of the loose parts, this approach can be easily expanded to wider identification problems including the estimation of mass, velocity, shape, and so on.

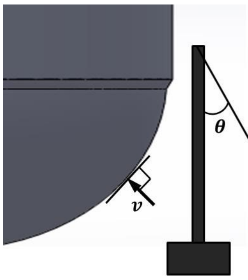
2. Impact wave propagation: experiment and simulation

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. The experimental testbed for the wave propagation test is presented in Figure 2.

Figure 2. Experimental testbed

A primary head of half scale SG made of 304 stainless steel was presented in Figure 3(a). 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 3(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.

(a) Test facility



(b) Schematic diagram of impact test

(c) Steel ball used in the experiments

Figure 3. Experimental setup

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 4 shows a typical finite element mesh of the analysis target. 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 5 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 6. The center frequencies obtained by test and FEA were 11,268 Hz and 10,597 Hz, respectively, and showed 6 % difference.

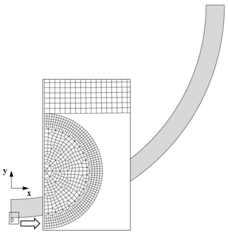


Figure 4. FEA model

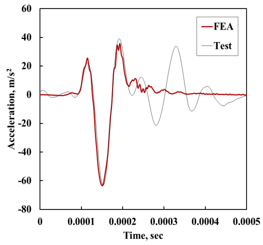
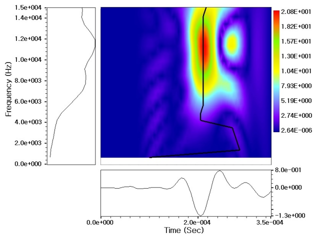
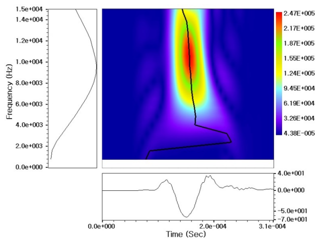


Figure 5. Acceleration response signals

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 modeling the loose-parts behavior in a nuclear power plant.



(a) Test



(b) FEA

Figure 6. Wigner-Ville distribution of acceleration response signals.

3. ANN based loose part localization

From the experiments conducted in the previous chapter, 120 sets of data are collected. This includes the combination of 6 levels of steel ball mass and 20 locations of ball impact on the primary head of half scale SG. In each test, acceleration signals are measured from ten points on the testbed, and time-frequency data is also used to train the ANN to establish the estimator for impact location. And from the FEA simulations, 360 sets of data are generated based on the approximate model.

Using 80% of acceleration signal and time-frequency data achieved from the experiments and FEA simulations, 5 layered ANN is trained to estimate the ball impact location. The combination of the time-frequency data and segmented time data are used as the input of the ANN, and the distance from sensors' location is defined as the output. The rest of the data is used to validate the result of ANN training. Table 1 shows the estimation results. Overall performance of the estimation showed 8% of difference or less. This is a meaningful result in the sense that it is a beginning phase of applying ANN to this kind of problem.

Table 1. Evaluation of the ANN Estimator

Impact Location (mm)		**Error**
Actual distance	Estimated distance (Averaged)	%
180	186	3%
200	204	2%
220	210	-5%
240	238	-1%
260	271	4%
280	285	2%
300	323	8%
320	329	3%
340	334	-2%
360	358	-1%
380	373	-2%
400	389	-3%
420	415	-1%
440	441	0%
460	472	3%
480	492	3%
500	527	5%
520	531	2%
540	547	1%
560	548	-2%

4. Conclusion

The localization of the steel ball impacting on the reactor pressure boundary structure are studied. Experimental and FEA based simulation studies are conducted to collect the acceleration response data. With the help of trained ANN, an estimator is built up to localize the impact on the structure.

We expect bigger size of the data to be accumulated over time, and in turn, this allows more precise training of the ANN for better and more accurate estimation performance in the near future. Even if this study is dealing with the localization of the loose parts, this approach can be easily expanded to wider identification problems including the estimation of mass, velocity, shape, and so on.

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