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Loose Part Detection Technique in Nuclear Power Plant Based on FE Simulation

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1. Introduction

The purpose of a loose part monitoring system (LPMS) is to detect unexpected objects in the primary coolant systems of pressurized water reactors (PWRs). There are two major goals in monitoring loose parts in nuclear vessels: (a) localization, which indicates the position of a loose part that may exist in the primary coolant system, and (b) mass estimation of the loose part. There are some successful approaches for localization such as the hyperbola, circle, and the triangular intersection methods [1]. However, an additional study for the mass estimation of a loose part is still required.

To overcome the problems of conventional methods, a machine-learning technique [2] and model-based diagnostics [3] have been recently employed. Owing to the increase in computing power, a finite element analysis (FEA) method has become an available option to calculate the impact response behavior for a real large structure, and has the advantage that evaluation can be conducted while considering the realistic geometry of the structure.

The purpose of this study is to review FEA-based model for localization and mass-estimation. An FEA model to simulate the propagation behavior of the bending wave generated by a metal sphere impact is validated by performing an impact test and a corresponding FEA for a downsized steam-generator structure. It is expected that the proposed FEA-based model can be utilized in model-based diagnostics for the estimation of impact parameters such as the mass, velocity, and impact location of a loose part. The FEA-based model can be used to optimize the sensor position to improve the collected data quality in the site of nuclear power plants.

2. Technical Background

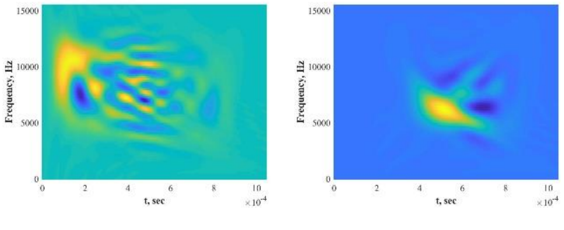
When a loose part impacts the inner boundary of a plate-like structure, such as pressure vessels and piping, mechanical bending waves are generated that then propagate through the structure. The bending waves are measured with accelerometers placed on the outer boundary of the structure. Conventional methods for the mass estimation use an analytical solution and simplified input geometry such as a flat plate. One of the most commonly used conventional methods for the mass estimation uses a metal sphere signal map, in which the center frequency and amplitude of the bending wave signal obtained by Hertz's impact theory and Lamb's general solution are used as important parameters. If, however, there are obstacles between the impact location and the sensor position, the measured signal becomes distorted and it makes it more difficult to estimate the loose-part mass with the simplified analytical solutions. As an example, Fig. 1 shows the Wigner–Ville distributions (WVDs) of impact signals calculated around obstacles such as a nozzle in a quarter-scale SG. The center frequency (f_c) obtained from WVDs was changed according to the sensor positions (or the geometry change).

Therefore, it is believed that the realistic geometry of the structure should be considered to estimate the accurate impact response behavior.

3. Loose Part Impact Simulation

3.1 Impact Wave Propagation Simulation

The impact wave propagation behavior in the plate-like structures was estimated through elastic FEA, and the results were then compared with the corresponding experimental results. The FEA was performed with an implicit solver in the ABAQUS Version 6.14 package. Fig. 2(a) shows a configuration and a finite element mesh for a 1/4 downsized SG. The mesh was constructed with approximately 1.5 million 20-node solid elements, C3D20R (20-node quadratic brick, reduced integration element) in ABAQUS. As an efficient way to simulate the metal sphere impact load onto the SG, the equivalent load for the metal sphere impact was applied as described in Ref. [3]. The acceleration data were stored at a sampling rate of 200 kHz.



(a) (b)

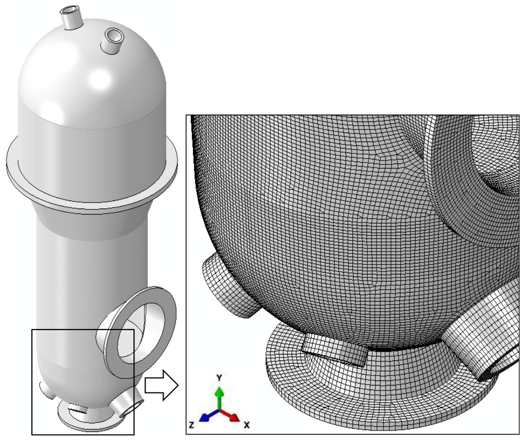
Fig. 1 Change of Wigner–Ville distribution according to the change in geometry: (a) Without geometry change (f_c = 11 kHz), and (b) Around nozzle (f_c = 6 kHz)

3.2 Simulation Results

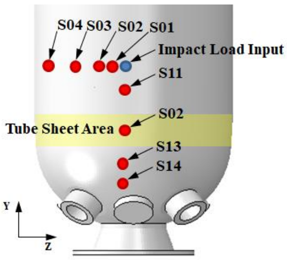
Fig. 2(c) shows the lower part of the SG used for impact tests and analyses, indicating the impact load input position and the acceleration sensor positions. The impact load was entered at 245 mm away from the top of the tube sheet, and the acceleration was then measured with accelerometers attached in both the horizontal (S01

~ S04) and the vertical (S11 ~ S14) directions. Fig. 3 shows the calculated and measured impact responses for the downsized SG, which are filtered with a low-pass filter with a cut-off frequency of 15 kHz.

Table 1 lists the signal properties (or feature vectors) such as the center frequency (f_c), and the amplitude (A) of the impact signal (which are commonly used for loose-part mass estimation) as well as the cross-correlation function (XCF) between the test signal and the simulated signal, which is proposed for loose-part mass estimation in this research. XCF is a measure of the similarity of two signals, and the amplitude (A) is defined as the peak-to-peak value of the time-acceleration signal. All calculated signal properties in the table were normalized with the test results. The FEA results of the amplitude showed a good agreement with the test results within a 30 % difference. The center frequency obtained from the tests and the FEAs are in good agreement within a 13 % difference.

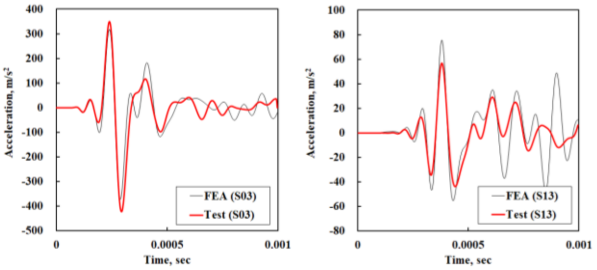


(a) Finite element mesh



(b) Impact load input position and sensor positions

Fig. 2 Finite element mesh for a 1/4 downsized steam generator



(a) S03 (b) S13

Fig. 3 Acceleration response signals of the impact wave at S03 and S13

A novel methodology to estimate the impact location and mass of a loose part is going to proposed, which is based on the amplitude (A) and the XCF between a simulated signal and a measured signal. The details are described in the next paper. When the XCF is used, data are analyzed in the time domain without any data conversion to the frequency domain, thereby making it possible to eliminate some problems that may occur in the frequency analysis. In addition, the XCF, as shown in Table 1, shows the reliability of equivalent levels with other impact parameters.

Table 1 Signal property estimates normalized with test results for identifying impact signal

Sensor ID	Normalized Center Frequency	Normalized Amplitude	Cross-correlation
S01	1.05	1.05	0.98
S02	1.02	1.02	0.95
S03	1.12	0.89	0.93
S04	1.05	0.84	0.93
S11	1.06	1.13	0.96
S12	1.03	1.12	0.98
S13	1.13	1.30	0.94
S14	1.02	1.10	0.83

4. Conclusions

In this study, an FEA model to simulate the propagation behavior of the bending wave generated by a metal sphere impact is validated by performing an impact test and a corresponding FEA for a downsized steam-generator structure. In addition, a new feature vector, the XCF, was proposed to predict the impact location and mass estimation of a loose part. The proposed FEA-base model will be used to estimate the impact parameters by applying machine-learning techniques, and to optimize the position of sensors to improve the data quality in the site of nuclear power plants.

Acknowledgement

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