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An Automatic Diagnosis Method for Impact Location Estimation

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Abstract

In this paper, a real time diagnostic algorithm for estimating the impact location by loose parts is proposed. It is composed of two modules such as the alarm discrimination module (ADM) and the impact-location estimation module(IEM). ADM decides whether the detected signal that triggers the alarm is the impact signal by loose parts or the noise signal. When the decision from ADM is concluded as the impact signal, the beginning time of burst-type signal, which the impact signal has usually such a form in time domain, provides the necessary data for IEM. IEM by use of the arrival time method estimates the impact location of loose parts. The overall results of the estimated impact location are displayed on a computer monitor by the graphical mode and numerical data composed of the impact point, and thereby a plant operator can recognize easily the status of the impact event. This algorithm can perform the diagnosis process automatically and hence the operator's burden and the possible operator's error due to lack of expert knowledge of impact signals can be reduced remarkably. In order to validate the application of this method, the test experiment with a mock-up (flat board and reactor) system is performed. The experimental results show the efficiency of this algorithm even under high level noise and potential application to Loose Part Monitoring System (LPMS) for improving diagnosis capability in nuclear power plants.

1. Introduction

LPMS is a diagnostic system that monitors the integrity of Nuclear Steam Supply System (NSSS) and analyzes the impact event caused by moving or loose parts. This system provides the necessary information for the operator's proper decision to maintain a reliable and safe Nuclear Power Plant. The loose parts, that are metal pieces, are produced by being parted from the structure of the reactor coolant system (RCS) due to corrosion, fatigue, and friction between components in RCS and also by coming into RCS from the outside during the period of reactor test operation, refueling, and maintenance in overhaul time. These loose parts are mixed with reactor coolant fluid, moved with high velocity along RCS circuit, and generate collisions with RCS components. When loose part strikes against the component within the pressure boundary, the acoustic impact wave is produced and propagates along the pressure boundary. For detecting the impact signal, conventional LPMS uses the accelerometer sensor installed on the outer surface of the pressure boundary of RCS components and announces the alarm when the detected impact signal exceeds a certain level which is pre-set by the operator. The sensors are usually installed on the probable places where loose parts may be collected or existed such as the upper head of the reactor pressure vessel, hot chamber of the Steam Generator[1]. Fig.1 shows a typical arrangement of sensors mounted on the outer surface of the major components of the NSSS, where the sensor locations are marked with a block circle.

In the existing LPMS, the alarm is triggered in the case where the signal threshold is exceeded by the measured signal and the detected signal is recorded on the magnetic tape. Later, the experienced operators analyze the recorded data and determine whether the detected signal is an impact signal by a loose part or noise signal. If their decision is concluded that loose parts caused the signal, they evaluate the characteristic parameters such as impact location, energy, and mass. After the diagnosis process mentioned above is completed, the proper procedure required for maintaining the safe and reliable operation is performed. In the conventional diagnostic method in LPMS, the operators should have expert knowledge for diagnosing the impact signal in order to execute proper action. Moreover, it takes a long time to analyze the detected signal data and hence possibly fatal damage of components may occur during the analysis procedure. Therefore, it is very desirable that if the alarm is triggered by a loose parts impact, the detected signal is stored in the computer memory, the automatic diagnosis procedure is activated immediately, and displays the diagnostic results such as location, mass, and energy of loose part in the operator's monitors.

Various methods for improving conventional LPMS have been presented [2-5]. Some of them were implemented in the nuclear power plant monitoring system. However, operator's diagnosis procedure for each impact signal is still required and needs the experienced knowledge for impact signal. In this study, the automatic diagnosis algorithm for estimating the impact location by a loose part is developed. This method is applied to the tests of alarm discrimination and impact location estimation with a mock-up facility for its verification. The experimental results show the good performance of the diagnosis algorithm even under high-level background noise.

2. Description of the Estimation Algorithm

The automatic estimation algorithm for impact location is composed of two modules, i.e., the alarm discrimination module(ADM) and the impact-location estimation module(IEM). The alarm in a conventional LPMS is triggered when the signal measured by an accelerometer installed on the outer surface of major components in NSSS exceeds the threshold level that is given by the operator for each sensor channel. The signal data before and after the alarms occur should be stored in computer memory for all sensor channels. In the operation of a nuclear power plant monitoring system, alarm triggering occurs due to a peak signal in the background noise, an amplitude increase by component operation such as control rod movement or pump operation, and an impact by a loose part. Due to background peak signal, these signals caused the false alarm. These signals that trigger the alarm are of different characteristic form. The triggering signal by background noise is a peak signal and is distinguished easily from the impact signal. The signal by component operation has a similar form as the impact signal but its rising and falling times are much longer that that of impact signal and the arrival time-difference between the sensors is very short. The shape of the impact signal by the loose part usually has a burst-type signal and its typical form is shown in Fig. 2. As can be seen in Fig 2., the rising and falling times of the impact signal are nearly proportional to the distances between sensors and impact locations, while peak amplitude decreases as further.

The ADM[6,7] using each channel's threshold determines whether the detected signal that triggers the alarm is the impact signal of the loose part or the noise signal. Also, the ADM calculates the beginning time (impact start point) for each of sensor signals data recorded.

The IEM[8] performs the estimation of the impact location by use of the arrival time method. This method can be used if more than three sensors are installed within the system (for example, Steam Generator or Reactor). Fig. 3 shows the flowchart of the developed algorithm and the details of each module is described in the following.

2.1. The Alarm Discrimination Module

The ADM is used to operate the alarm discrimination function. In order to distinguish the alarm by the impact signal from that by the noise signal, ADM is designed to compare each channel's threshold to the current value and the evaluation criteria. For example, it is assumed that the total N data samples are stored in computer memory for every sensor channel when the alarm system is activated. Let x(n) be the signal at the sample point n ($1 \le n \le N$) and n_s be the beginning point of impact signal. The average of the signal level, $\bar{x}$, in time domain is defined as

$$\bar{x}(n) = \frac{n \times \{\bar{x}(n-1)\} + |x(n)|}{n+1}, \quad n=1,\cdots,N \quad (1)$$

The alarm point n_p is determined under the following condition,

$$|x(n_p)| > \lambda_{threshold} \quad (2)$$

where $\lambda_{threshold}$ is the threshold value of each channel and is highly dependent on the level of background noise. Because the values of $\lambda_{threshold}$ are different from each channel, the proper value per sensor channel is to be determined in order to evaluate accurately the alarm event. This is very time-and-effort consuming work when it is determined based on the operator's trial and error method. In this work, a systematic approach for calculating the appropriate value of $\lambda_{threshold}$ with the consideration of noise level in each sensor channel is suggested.

To find $\lambda_{threshold}$, we first collect M_S ($M_S \ll n_s$) data samples corresponding to the pure noise signals and compute l as

$$l(n) = \frac{\left||x(n)| - \bar{x}(n)\right|}{\bar{x}(n)}, \text{ n=1,}\cdots\text{,M}_S \quad (3)$$

where $\bar{x}(n)$ is the moving average of x(n) as in (1). The maximum value of l(n) is given by,

$$l_{\max} = \max_{1 \le n \le M_S} \{l(n)\} \quad (4)$$

resulting in the inequality condition

$$|x(n)| \le (l_{\max} + 1)\bar{x}(n) \quad (5)$$

Note that (5) is always satisfied for all signals in the interval of [1, M_S]. In order for (5) to be applicable in the interval of [M_S, n_s], the right hand side of (5) is modified terms so that

$$\lambda_{threshold} = \{\ (1+\gamma_s)l_{\max} + 1\ \}\bar{x}(n) \quad (6)$$

where γ_s is a constant between 0.02 and 0.05. The condition in (2) is usually satisfied by the impact signal but sometimes the peak signal in background noise satisfies this condition. In order to distinguish the effect by the impact signal from that by the peak noise signal, another condition (evaluation criteria) for identifying the impact signal is supplemented. Let $\bar{x}(n_s)$ be the beginning point of impact signal. From this point, we choose $\bar{x}(n_s+1), \ldots, \bar{x}(n_{\text{int}})$ where the sample interval(window), [n_s+1, n_{int}], is to be determined properly from an operator according to the sampling rate of each sensor signal. Within the interval of [n_s+1, n_{int}], the minimum value of $\bar{x}(n)$ be $\bar{x}_{\min}(n)$. The supplementary condition for evaluating the alarm point is that if

$$\bar{x}_{\min} > \lambda_{threshold} \quad (7)$$

then it is concluded that the condition in (2) is triggered by the impact signal and finally the value of n_s is stored because this value returns to the IEM.

2.2. Impact-location Estimation Module

The characteristic parameter extracted from ADM is the beginning times of the impact signal. The beginning time is used in the IEM in order to calculate the impact location and hence it is essential that the beginning time is estimated accurately. From Fig. 2, when the impact signal arrives at the sensor, the amplitude of signals read in the sensor increases rapidly and reaches the maximum value in a short time. After the maximum value of the amplitude of impact signal is reached, the signal begins to decay out.

There are two methods to determine impact point ; Arrival time method and Wave mode method. The arrival time method is used for more than three sensors. Otherwise, the wave mode method may be used[7]. The underlying principle of the arrival time method is that the arrival time of the impact signal is proportional to the distance between sensors and the impact point. So, from the distance gap of the two sensors, we can draw the hyperbola line. And the meeting point of three lines is the impact point. Fig. 4 shows the evaluation method of the arrival time differences. That is,

$$r_1 - r_2 = V_g \cdot \Delta t_{1,2}$$
$$r_2 - r_3 = V_g \cdot \Delta t_{2,3} \quad (8)$$

where r_1, r_2, r_3 are the distances between each sensor and impact point and V_g is the wave group velocity. $\Delta t_{1,2}$ is the time difference between sensor #1 and sensor #2 and also $\Delta t_{2,3}$ the time difference between sensor #2 and sensor #3. In general, V_g depends on the structure.

3. Experimental Results

To apply the developed algorithm to the impact sources, we gathered the impact signal from the mock-up systems. The first one is the flat board that is made of the same material with reactor and has the following dimensions: the breadth (2 m), the length (1.6 m) and the thickness (2.5 cm). From this flat board, we collected the impact signal by an impact hammer. Table 1 shows the results after running the developed algorithm and comparing the impact point to the estimated impact point. Fig. 5 shows the 1st experimental result using the developed algorithm. And Fig. 6 shows the 2nd experimental result. From Fig. 5 & 6, we see that this estimated points are fairly in accord once with the impact points. Second, we applied to the reactor mock-up system. Fig. 7 shows the reactor mockup whose size is scaled down to 1/7 and thickness is 10 mm. From Fig 7, this reactor system is divided into two parts; cylindrical and spherical part. So the coordinates transformation is needed. Fig. 8 shows the result when the impact point is in the middle, and compares the estimated point (3°, 479) to the impact point (0°, 467) in cylindrical system. And Fig. 9 shows the result when the impact point is in upper head, and compares the estimated point(R, 52°, 37°) to the impact point(R, 50°, 30°) in a spherical system through the developed algorithm. From the results, the estimated locations agree well to the impact points.

4. Conclusion

In the conventional diagnostic method in LPMS, the operators should have expert knowledge in diagnosing the impact signal in order to execute immediate proper action. Otherwise, it takes a long time to analyze the detected signal data and possibly fatal damage to components may occur. To reduce the time needed to analyze the detected signal data, we presented an automatic impact location estimation method and applied the developed algorithm to the flat board and the reactor mock-up system. From the experimental results, it has been shown that the estimated point comparing to the impact point was within the error bound of 10 %. To apply the developed algorithm to the LPMS of the existing plant, it will be necessary to test this algorithm with the actual impact signals and some modification may be needed because we do not consider explicitly the operation conditions of plant. Further research topics of interests are performance improvement by introducing noise cancellation techniques, treatment of the case where less than three sensors are installed, and so on.

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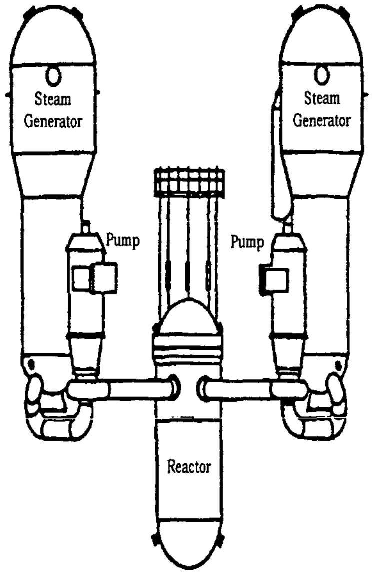


Fig. 1. The general sensor position of NSSS

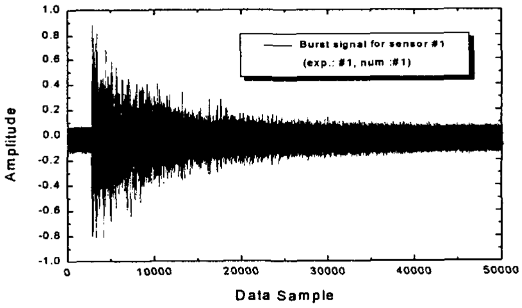


Fig. 2. The typical form for burst-type signal

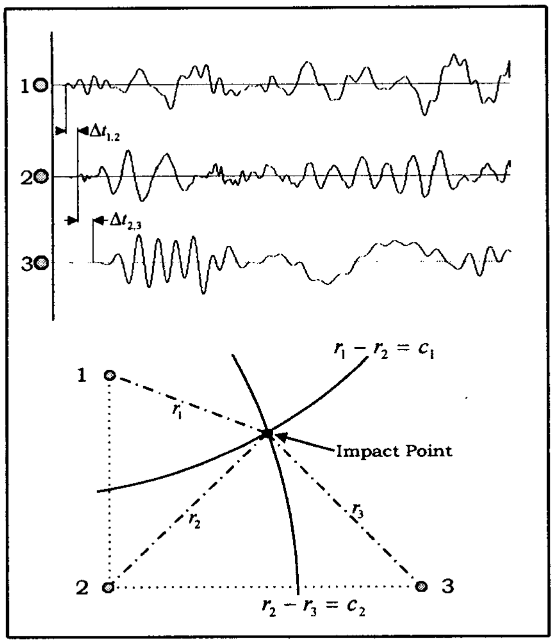


Fig 4. The evaluation method of arrival time differences

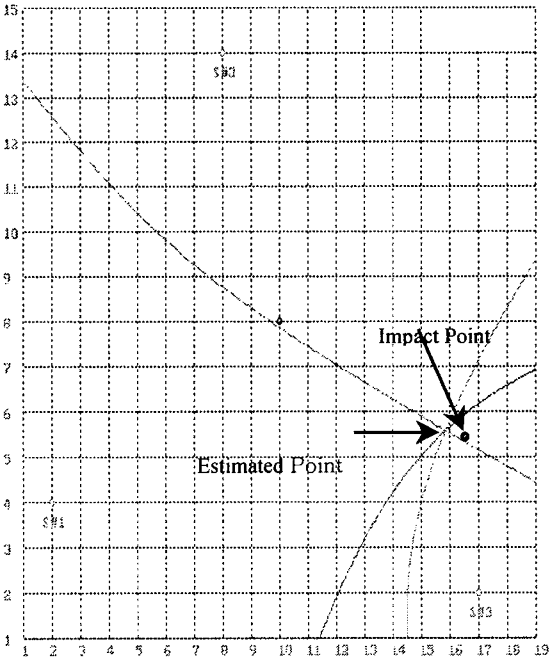


Fig. 5. 1st experiment result (flat board)

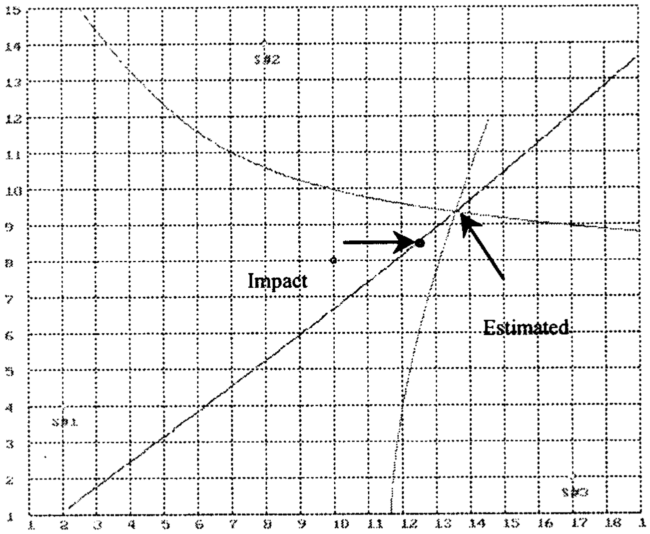


Fig. 6. 2nd experiment result (flat board)

Table 1. Comparison table between impact point and estimation point

Experiment Type	Experiment No.	Impact Estimation	Estimation Error
1st Experiment (16.5,5.5)	1	(15.6, 5.5)	9.0 cm
	2	(13.7, 5.1)	28.3 cm
	3	(15.6, 6.2)	11.4 cm
2nd Experiment (12.5, 8.5)	1	(13.5, 9.3)	12.8 cm
	2	(12.3,8.1)	4.4 cm
	3	(12.0,8.1)	6.4 cm

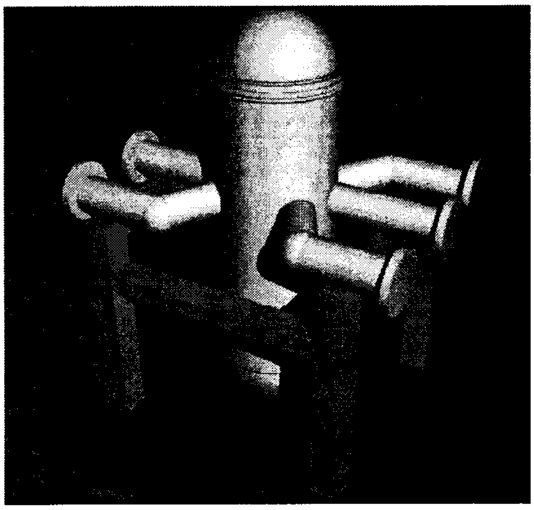
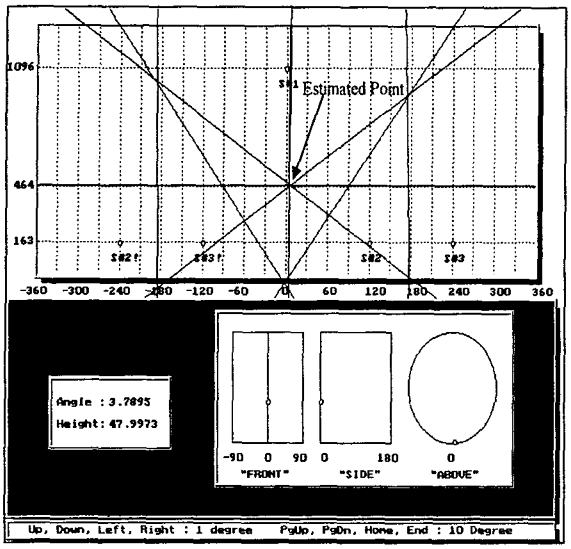


Fig. 7. Reactor Mock-up



Angle : 3.7895
Height: 47.9973

Up, Down, Left, Right : 1 degree   PgUp, PgDn, Home, End : 10 Degree

Fig. 8. Comparison of the impact point and estimation point in cylindrical coordinate

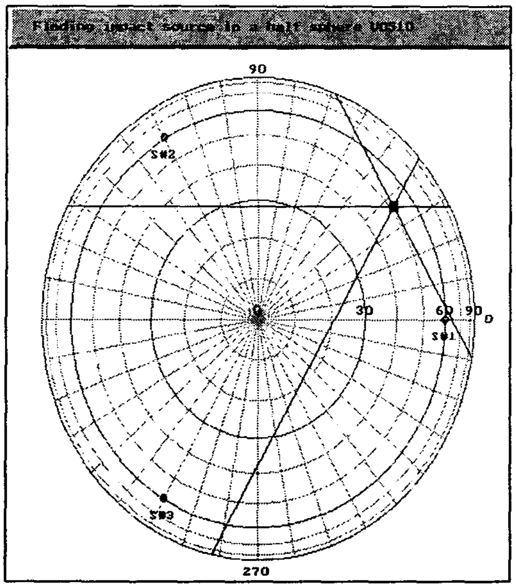


Fig. 9. Comparison of the impact point and estimation point in spherical coordinate

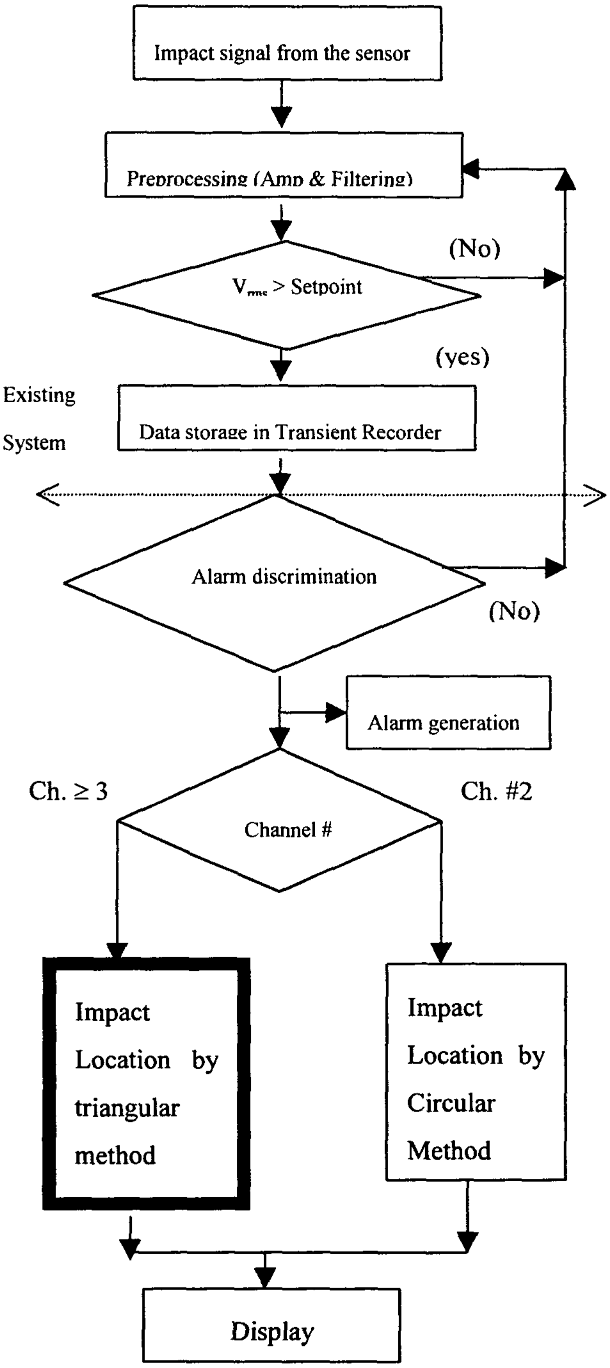


Fig. 3. The overall flowchart of developed algorithm