Acceleration Signal Characteristics for Intuitional Mass Analysis of Metallic Loose Parts

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1. Introduction

Nuclear power plants (NPPs) have operated LPMS (Loose Parts Monitoring System) for early detection of the possible presence of metallic parts in the reactor coolant system (RCS); however, analysis of the metallic impact wave characteristics in the LPMS is an important issue because information, such as the mass of the metallic part and the impact location, is not provided. For the analysis of a metallic impact signal, experience in variable signal analysis, physical understanding of the metallic impact signal, and knowledge of accelerometer installation locations and the steam generator structure are necessary. Most studies have concentrated on fieldwork using the frequency characteristics for the analysis of the metallic part mass. Thus, the field engineers cannot analyze signals without special software and access to the system.[1][2] This paper is intended to introduce a process of intuitional mass analysis using the attenuation rate of the acceleration signal and the intervals between peak signals.

2. Theory of metallic impact signal

The theory of metallic impact signal, based on Hertz's metal impact theory, is a technique to estimate the mass of metallic parts by evaluating the frequency characteristic from the acquired acceleration signals and generated impact waves when metallic parts impact the reactor and the steam generator pressure boundary inner surface. Hertz's metal impact theory applies Newton's second law of motion, which will come into effect under the assumption that the movement of the contact area is an elastic contact and that a steel plate is much bigger than a steel ball when the steel ball falls free on the isotropic steel plate. This theory provides the theoretical basis to analyze the acceleration signal of the LPMS.

Assuming that the main response of the steel plate is a bending wave of half of the impact contact time, the maximum displacement D_{max} and the contact time T_d during the impact, based on Hertz's metal impact theory, can be expressed below,

$$D_{max} = Kh(mV_o^2)^{0.4}R^{-0.2} \qquad (1)$$

$$T_d = 2.94\, D_{max}/V_o \qquad (2)$$

$$\text{where, } Kh = \left[\frac{15}{16}\left(\frac{1-V_1^2}{E_1}+\frac{1-V_2^2}{E_2}\right)\right]^{0.4}$$

m: mass of a steel ball ($lb_f/32.2ft/sec^2$)
Vo: impact velocity of a steel ball (ft/sec)
R: a steel ball radius(ft)
ν_1, ν_2: Poisson rate between a steel plate and a steel ball
E_1, E_2: Young rate between a steel plate and a steel ball (lb_f/in^2)

From these equations, the contact time can be seen to be dominantly related to the impact mass and the impact velocity. Furthermore, Raman (1920) has discovered that the initial half wave is 1.6 times shorter than the contact impact time. Consequently, the maximum amplitude can be seen at around the frequency related to the initial half wave at the impact acceleration spectrum; the equation is expressed below. The impact acceleration spectrum has a discrete characteristic at the ± 50% band of this frequency.[3][4]

$$F_a = 1.6/(2T_d) \qquad (3)$$

Therefore, in cases in which the metallic part mass is heavy, the characteristics, namely that the impact contact time is longer and the frequency is shorter, can be determined. Thus, this method has been utilized in a lot of a frequency analysis for mass analysis of metallic parts in the RCS. But, as NPPs have vibration in the reactor coolant pumps, due to friction between the coolant and the high pressure tubes during normal operation, it is difficult to analyze the mass of a metallic part through simple frequency analysis.[5]

3. Mass-specific frequency characteristics

As the impact contact time and the impact velocity of the metallic part in the NPP reactor coolant system are unknown, Hertz's impact theory cannot be used directly to analyze the mass of the metallic part. Thus, NPPs apply Equation (3) in order to analyze the mass of the metallic part.

Fig. 1. shows the mass-specific frequency spectrums during simulations using different steel balls at the steam generator primary side in the NPP.

The 10.8 kHz frequency in Fig. 1. is the noise energy that originated; it has no relation to the mass of the steel balls and is only due to NPP operation. The mass-specific characteristic energy is focused at around 11.6 kHz at 57 gram and 3 kHz at 1814 gram. Therefore, this experiment has proved the theory of Hertz and Raman, that the heavier a steel ball is, the longer the contact time and the lower the frequency it will have.

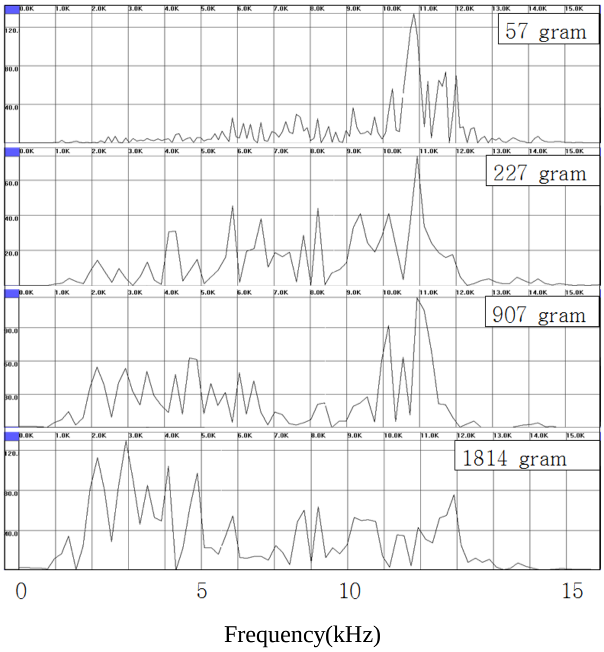


Fig. 1. Power spectral density for different ball masses.

4. Tests and results

In this section, simulations were performed in the NPP in order to standardize the mass-specific data, such as the attenuation rates and the peak intervals of the impact waves. By utilizing these data, it can be possible to predict the mass of various metallic parts.

4.1 Test conditions

To simulate impact conditions in which a metallic part is moved by the reactor coolant velocity, the impact energies could be generated by free falling of 57 g, 227 g, 907 g, and 1814 g objects, for a total of four different steel balls at 15 cm, 30 cm, 50 cm, and 60 cm heights, 3 ft of distance away from the accelerometer installed at the steam generator primary side in the NPP(OPR1000).

The equipment used to measure the impact signal is the LPMS. The LPMS is capable of 100 kHz sampling time and 16 bits resolution; it is only used to detect metallic impact signals.[6]

4.2 Mass-specific acceleration signal characteristics

When an existing metallic part in the RCS runs into the structure, the generated impact wave transfers the energy through the structure from one location to another location. The phenomenon of transferring energy impact wave is a wave motion. Wave motion is classified into longitudinal and transverse waves. A longitudinal wave is a wave in which the displacement of the medium is in the same direction of travel as the wave. A transverse wave is a wave in which the displacement of the medium is perpendicular to the direction of travel of the wave.

A longitudinal wave in which a relatively large energy is observed from the accelerometer, as compared to a transverse wave, has a propagation velocity of about 5200 m/s in the steam generator. A transverse wave has a propagation velocity of about 3100 m/s. As the accelerometer in the NPP has a sensitivity of less than 3%, transverse waves cannot be well detected by the accelerometer.

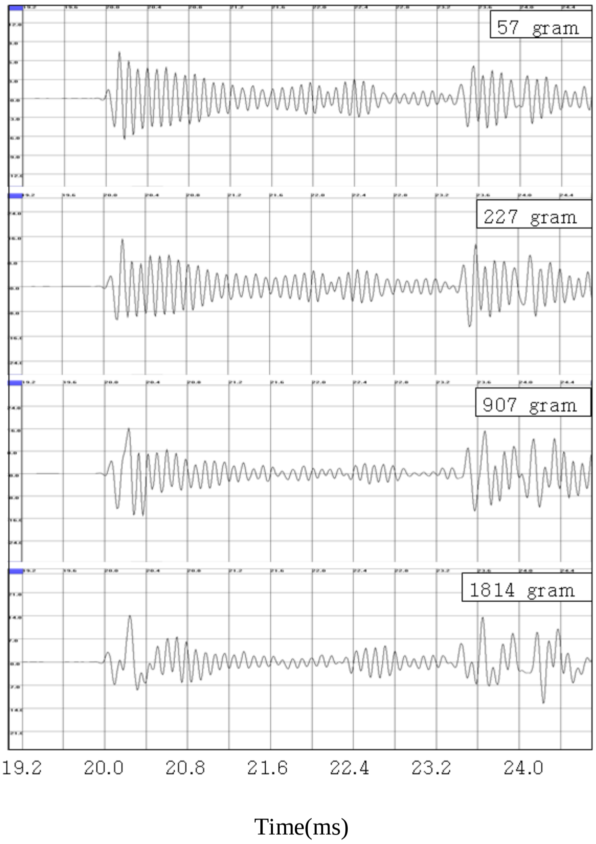


Fig. 2. Time chart for different ball masses.

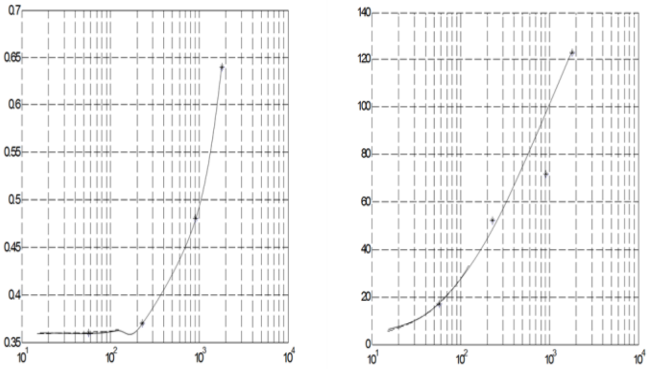
Signals are observed between 20.0 ms and 20.4 ms, as shown in Fig. 2. Fig. 2. shows that the energy signal generated by the 57 gram steel ball decreased moderately from the peak signal to 20.4 ms; 5 peak signals are detected. For the 227 gram sample, the energy signal decreased irregularly compared to the energy signal generated by the 57 gram steel ball; 4 peak signals are detected. For the 1814 gram sample, the energy signal decreased irregularly and 2 peak signals are detected.

Most signals detected by the accelerometer installed on the steel plate are longitudinal waves; this is due to the accelerometer characteristics. In Fig. 2., data for the heavier impact mass is shown; it can be understood intuitionally that there is a transverse wave and a longitudinal wave that are mixing, widening the peak interval of the initial wave. Therefore, for mass analysis of a metallic part when the impact attenuation rate and the count of the peaks are quantified by using the mass-specific standard data, these will be useful data. To assemble mass-specific standard data, the attenuation rate (4) was acquired by calculating the rates between one positive peak value and the next positive peak value; the peak interval was the measuring time needed to obtain 5 positive maximum peaks. Table 1. shows the mass-specific attenuation rates and the peak intervals. Fig. 3. displays the data from Table I as a graphic, using the interpolation method. Through the simulation test, the mass-specific attenuation rates and the peak intervals have been proven.

$$\left[1-\left(\frac{Peak_{max2}}{Peak_{max1}}\right)\right]\times 100 \; = Attenuation\ Rate \quad (4)$$

Table I: Reference table for different ball masses

Ball Mass (gram)	Attenuation Rate (%)	Peak Interval (㎳)
57	17	0.36
227	52	0.37
907	72	0.48
1814	123	0.64



a) Attenuation Rate b) Peak Interval

Fig. 3. Reference Curve for different ball masses

5. Conclusions

Most studies related to mass analysis of a metallic part impact signal in LPMS have used the frequency spectrum. This paper presents a method of using the acceleration signal characteristics for intuitional mass analysis of loose metallic parts.

With the method proposed in this paper, because the mass of a metallic part can be understood intuitionally without any special analysis program, intuitional analysis used in parallel with frequency spectrum analysis will be in effect.

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