A development of mass estimation tools based on pre-operation test for the Loose part monitoring system of OPR-1000

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1. Introduction

A loose part, located in the react coolant system (RCS) of nuclear power plant (NPP) and circulates with coolants, can cause damage to the component of the RCS by impacts on the components and threaten the integrity of RCS system, so that a reliable means, such as Loose Part Monitoring System (LPMS) of OPR-1000 as shown in figure 1, should be provided to detect a loose part for securing the safety of the NPP. The detection of a loose part is performed by evaluation of the loose part location and its mass using acceleration signals, which are generated by the impact of the loose part on the component and measured with the sensors attached to the outside surface of component.

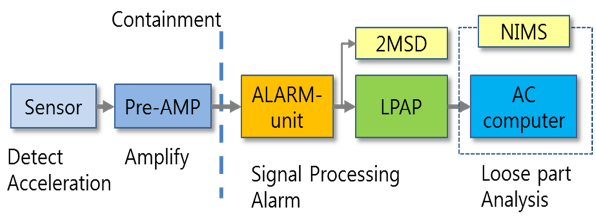

Fig. 1. The schematic diagram of the major components of LPMS of OPR-1000

The impact source localization and mass estimation technique have been two crucial issues for the detection and diagnosis of a loose part in NPP. Conventionally, center frequency and frequency ratio technique have been widely used for a mass estimation. While most of mass estimation techniques have been developed and successfully applied in well-defined condition as like laboratory experiments, in a complex and noisy environment, practical and reliable tools are definitely necessary.

In this study, utilizing the conventional techniques, practical mass estimation tools have been developed based on the field test data which were obtained from the pre-operation test of LPMS in construction stage of OPR-1000 reactor.

2. Mass Estimation Technique

2.1 Analytical Method based on Hertz contact Theory

Based on the Hertz theory, the impact contact time t_h can be expressed as [1],

$$t_h = 2.95\, k_h\, M^{0.4}\, V^{-0.2}\, R^{-0.2} \tag{1}$$

where, k_h is a material constant which is a function of the Young's modulus and Poisson's ratio of plate and impacting object, M and V is a mass and velocity of impacting object, respectively. R is the radius of curvature at the contact point.

The impact force at the point of impact can be obtained from the associated the plate bending wave and it can be expressed as

$$F_{max} = \frac{8B^*|A_{PL}|_{max}}{C_b^2} \tag{2}$$

where, B^* is the plate bending stiffness expressed as $B^* = \frac{EI}{1-\nu^2}$, $A_{PL}$is the surface acceleration of the plate bending wave motion, and C_b is the plate bending wave velocity that can be calculated from

$$C_b = \sqrt[4]{\frac{B^*}{m}}\sqrt[2]{2\pi f_p} \tag{3}$$

where, m is the plate mass per unit surface area and f_p is the dominant frequency of the impact bending wave which can be determined from the frequency spectra of the impact response signal right after the impact.

Thus, the momentum of impacting object is obtained as

$$M\,V = \frac{F_{max} t_h}{\pi} \tag{4}$$

When the A_{PL} and f_p are obtain from the measured impact response signal, the contact time is calculated using the its inverse proportional relation to the dominant frequency of Lamb wave, $t_h = {}^{1.6}/_{2f_p}$.

The procedure to estimate the mass is to select the range of candidate mass based on the operating experience, and then impact force and the momentum is calculated using equation (2), (4) and given A_{PL} , f_p and t_h. Consequently the associated velocity is obtained from the momentum equation (4) and then the radius of curvature is calculated from the equation (1). If we choose only the reasonable radius of curvature with respect to the candidate mass, the acceptable range of candidate mass will be defined. Therefore, the estimated mass is defined as the mean values of the range of mass that is accepted.

2.2 Metal Sphere Mass Map

When the $A_{PL,max}$ and f_p are obtained from the impact response signal with the known impact mass and velocity, Metal Sphere Mass Map[3] can be plotted as figure 2 based on the field test data. The impact mass can be estimated by utilizing this diagram in the field.

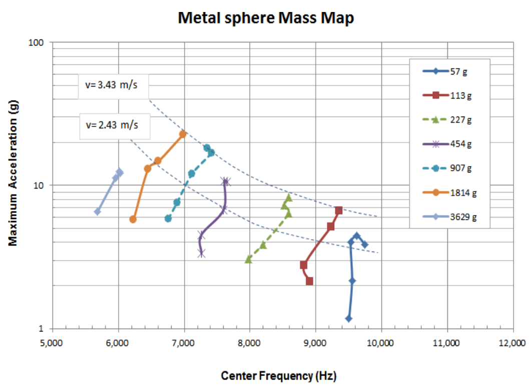

Fig. 2. Metal Sphere Mass Map for Channel #9 of LPMS of Shin-wolsung NPP unit 1.

2.3 Frequency ratio (FR) technique

The FR(Frequency ratio) for impact response signal *s(t)* is defined as [2]

$$\mathrm{FR} = \frac{\int_{1kHz}^{6kHz} S(f)\, df}{\int_{10\,kHz}^{15\,kHz} S(f) df}$$

where *s(f)* is an auto-power spectral density of *s(t)*. Since the signal power in the lower frequency range is proportional to the impact duration and the duration is also proportional to the impact mass, FR is a function of impact mass.

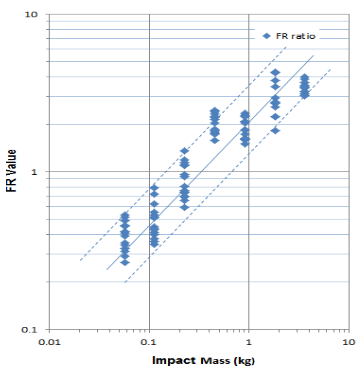

Fig. 3. FR diagram for Channel #9 of LPMS of Shin-wolsung NPP unit 1.

2.4 Center frequency (FC) technique

The center frequency f_c for impact response signal *s(t)* is defined as

$$f_c = \sum_i R_{fi} f_{ci} \Big/ \sum_i R_{fi}$$

where, $R_{fi} = \frac{S(f_i)}{B(f_i)}$ is a ratio of auto-power spectral density of *s(t)* to that of background noise *B(t)*. $f_{ci} = \frac{(f_{i-1}+f_i)}{2}$ is a center frequency at the *i*-th frequency interval. Therefore, center frequency means the area center of spectral function. Since the heavier mass induces long contact and lower frequency component, *fc* inverse proportional to the mass of impacting object.

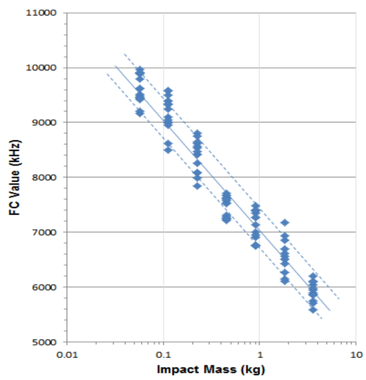

Fig. 4. *FC* diagram for Channel #9 of LPMS of Shin-wolsung NPP unit 1.

2.5 Best Matching technique

In phase 2 step of LPMS calibration test, impact response data for wide variety of impact energy at a specific points are gathered and archived. The best matching technique is currently implemented in LPMS of OPR-1000 NPPs. It is based on the phase 2 step calibration test data and measurement of signal properties including amplitude and frequency content.

3. Conclusions

The comparisons with the accuracy and uncertainty of the mass estimation technique lead some remarks as follows:

- Mass estimation is more sensitive to f_p and/or t_h.
- By using the momentum of impacting object to define valid combination of mass and velocity, it is useful to reject unlikely contact radius of curvature with this constraint.

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