A method of locating loose parts in nuclear power plant based on empirical mode decomposition

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Location of loose parts can be calculated by the propagation velocity of flexible wave and the time differences from different acceleration sensors gained from original signal wave shape. But the start point is often influenced by the frequency dispersion of flexible wave in propagating medium and the different regression rate among frequency components. A new method of locating loose parts based on EMD（Empirical Mode Decomposition）is proposed in this paper. EMD decomposes the signal into a series of IMF(Intrinsic Mode Function), one of which is selected to be the research object. Wavelet transform is applied on the given IMF to make its frequency purer. The impact position is calculated based on the start point of the chosen IMF and wave velocity obtained by the dominant frequency and the propagating medium. Simulation experiment that carried out to verify the proposed method proves that the method is reliable.

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1. Introduction

As one of the new resources, nuclear energy has got vast attention and application in many countries all over the world. Due to the high energy and radiation of nuclear fuel and long-term operation under high temperature and high pressure condition, ensuring the security of the nuclear power plant is of great significance. The pressure vessel and the prime circuit of the nuclear reactor are filled with high temperature and pressure coolant water that takes charge of transforming reaction heat and cooling the core. Scoured by cooling water, the components and parts inside the pressure vessel of nuclear power plant is inevitably led to loose from their original position and even drop which brings latent menace to the security of nuclear power plant. Loose Part Monitoring System (LPMS) is designed to detect the abnormal condition of nuclear reactor and analyze the detected signals. Location of loose part contains helpful information that helps operators and technicians make corresponding optimal decision to cope with the abnormality in time so as to get the condition under control and reduce the probable loss. Thus locating of loose parts is one of the most important functions of LPMS.

Methods of locating the loose part which attracts researchers from many countries are usually divided into three kinds[1-5]: first is time difference of arrival (TDOA) method or called triangular locating method, the second is circle intersection method and the third is grid scan method. The methods of TDOA are all based on the signal start point of the vibration wave detected by different sensors. It calculates the impact position by using the pre-measured wave velocity and the time differences based on start point. The accuracy is affected by the bias of the measured velocity and the position of the start point. Circle intersection utilizes the time-frequency analysis to acquire the time-frequency distribution of the signal. The impact position can be obtained as the intersection of the circles whose radius are calculated using the propagating times of different frequency components. But the exact time-frequency features which is often difficult to confirm needs to be picked manually. The coordinate scan method is also based on the start point of the signal in time domain but the measurement of wave velocity is needless. The impact position can be obtained by scanning all the coordinates of a certain interval. It costs much time when the range of the coordinate system is large such as the real pressure vessel wall.

The constitution of the elastic wave originated from the impact occurred between the loose part and the wall of the pressure vessel is very complex, including longitudinal wave (pressure wave), transverse wave (shear wave), bending wave and other kinds of waves. With the property of frequency dispersion, the elastic wave propagating in the reactor structure consists of many components with different frequencies. Propagation through different distances, wave form of the elastic wave is effected by different regression rate of different frequencies, the scattering, reflection wave and structure resonance due to the complexity of the reactor. The signal in time domain still contains some kind of unpredictable noises such as electrical pulses that disturb the procedure of picking a right starting point of the signal even if having been processed using some kind of denoising method. The measured wave velocity, which is measured through the testing distance and the starting point position of the testing signal on the same medium, can possibly calculated with bias before location calculating. Accuracy of locating a loose part is therefore influenced by the error of the starting point and the measured wave velocity while using traditional locating method.

A new method based on EMD (Empirical Mode Decomposition) to locate loose part is proposed in this paper. The locating method by use of time difference of arrival locating method, the theory of EMD and the processing of refinement by wavelet is stated in section 2. Simulated experiment, results of data processing and the conclusion are illustrated from section 3 to section 4 respectively. Data analysis of Simulation experiment of loose part impacting proves that the method proposed above is feasible.

2. New method based on EMD to locate loose parts

2.1 Theory of time difference of arrival locating method

TDOA location method is also called triangular method for that three acceleration sensors are installed on certain positions to form a triangle. The relative time differences among the sensors are obtained based on the wave arrival times of each sensor and a chosen sensor among them. The position of the impact instance can then be estimated by solving a relative function using the time differences and the measured wave velocity.

Three acceleration sensors S_1 (x_1, y_1), S_2 (x_2, y_2) and S_3 (x_3, y_3) are installed on the vertexes of a triangle as shown in Fig.1.

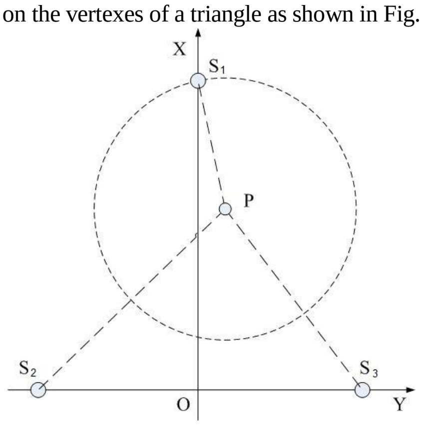

Fig. 1 The scheme of position of the acceleration sensors and the impact position

Assuming that the impact happens at P (x_p, y_p) and the nearest sensor is S_1. The relation equation of the positions of the vertexes and the impact position can be obtained based geometrical relationship.

$$\begin{cases} \overline{PS}_2 - \overline{PS}_1 = c\Delta t_{12} \\ \overline{PS}_3 - \overline{PS}_1 = c\Delta t_{12} \end{cases} \tag{1}$$

Where $PS_i = \sqrt{(x_p - x_i)^2 + (y_p - y_i)^2}, i = 1,2,3$ represents the distance between the impact position and the sensor *i*.

Fig. 2 shows a scheme of the detected signals. The vertical lines in graphic represent the position of the start point.

Thus the corresponding arrival times of each sensor are t_1, t_2, t_3 respectively. Take S_1 as the referred sensor, time differences are described as

$$\begin{cases} \Delta t_{12} = t_2 - t_1 \\ \Delta t_{13} = t_3 - t_1 \end{cases} \tag{2}$$

The coordinate of the impact position is then acquired by solving the equation set above.

The position can also be obtained by solving a hyperbolic equation set that consists at least two hyperbolas whose focal points are the vertexes of the triangle according to the definition of the hyperbola that the difference of the distance from impact position to the two sensors keeps invariant. The right solution can then be picked out by the time difference from two or more possible intersections. The intersection point of the hyperbola with focal point of {P1,P2} and other hyperbola of {P1, P3} is the practical impact position in the scheme, e.g.

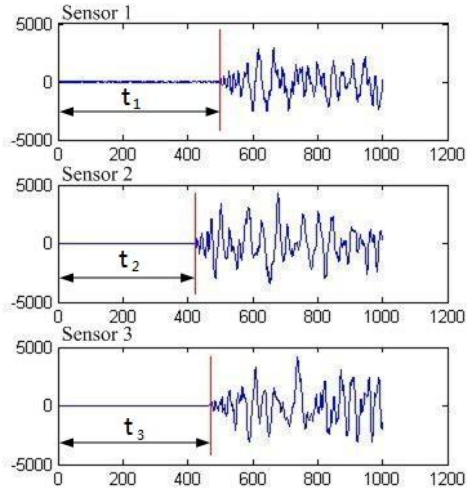

Fig. 2 Arrival times of different signals

2.2 Process of Empirical mode decomposition

Empirical mode decomposition (EMD) is part of Hilbert-Huang Transform invented by Norden E. Huang[6,7]. It is designed for analysis of nonlinear non-stationary signals which are normally hard to analyze for their properties of time-varying and complex frequency contents. EMD is based upon the assumption that signal of any form consists of several different Instinct Mode Functions(IMF) which represent the instinct vibration modes of the original signal. Compared to Fourier decomposition, it transforms a time-domain signal into limited components from high frequency to the low frequency.

EMD decomposes the nonlinear non-stationary time-series signal into a collection of stationary and linear series set called intrinsic mode functions (IMF) but not several sine or cosine functions as Fourier transform does. The IMF are defined under two constrain conditions: 1. the number of extreme and zero crossings must either equal or differ at most by one in the whole signal series; 2. the mean value of the envelope fitted by the local maxima and the envelope fitted by the local minima is zero at any point of the data. The essence of EMD is to analyze the given signal using the intrinsic vibration mode obtained based on the feature time scale of the signal. So this method is capable to process both the linear stationary signals and the nonlinear non-stationary signals.

Steps of acquiring the first IMF of a signal are illustrated below.

1) EMD firstly seek the local extreme point of the original time-series signal $x(t), t = 1,...,n$. Then the envelope lines of the signal named $u_1(t)$ and $l_1(t)$ are obtained by curve fitting using maximum and minimum extreme points respectively. Average series $m_1(t)$ is defined as the mean value of $u_1(t)$ and $l_1(t)$ at every point.

$$m_1(t) = \frac{u_1(t) + l_1(t)}{2} \tag{3}$$

2) Calculate the difference between the original signal and the average series.

$$c_1(t) = x(t) - m_1(t) \tag{4}$$

$c_1(t)$ can be the first IMF if $x(t)$ is an harmonic signal. But $c_1(t)$ is unable to satisfy the IMF constrains conditions usually. So more calculation is required which replace the original signal $x(t)$ in (2) with $c_1(t)$ and repeat the process from calculate the envelope lines to the renewed equation (2) with $c_1(t)$. The process keeps repeating until the k th average series matches the IMF conditions and the first IMF $c_{1k}(t)$ of the signal is therefore obtained.

$$c_{1k}(t) = c_{1(k-1)}(t) - m_{1(k-1)}(t) \tag{5}$$

The first IMF is subtracted from the original signal as

$$x'(t) = x(t) - c_{1k}(t) \tag{6}$$

Then the second IMF can be calculated on the basis of the series $x'(t)$ excluding $c_{1k}(t)$ using the same procedures above, so as the rest of the IMF.

Practically, extracting the IMF from a complex impact signal abiding the IMF conditions strictly consumes tremendous amount of time. And it is necessary to limit repeating times so as to prevent all the IMF become a frequency modulated signals with constant amplitude. The stop times of the calculation can often be decided by the empirical formula.

$$SD = \frac{\sum_{t=1}^{n} \left| c_{1(k-1)}(t) - c_{1k}(t) \right|^2}{\sum_{t=1}^{n} c_{1(k-1)}^2(t)} \tag{7}$$

Here, SD, which is the threshold of the calculation, is usually set to 0.2-0.3. The calculation of extracting one IMF finishes once the SD is less than the threshold.

The extracted series is considered to be the residual component $r(t)$ if the number of extreme point is less than two and IMF extraction is finished.

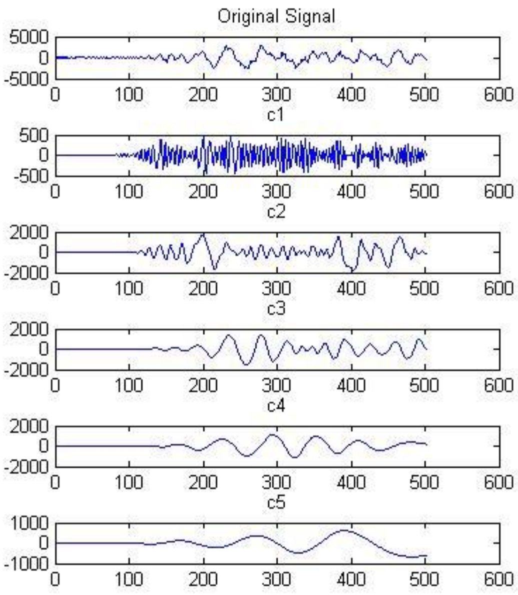

Fig. 3 signal and its IMF.

A collection of IMF and one residual component are obtained at the end of EMD processing. Hence a signal can be expressed by sum of its n IMF and one residual component.

$$x(t) = \sum_{i=1}^{n} c_i(t) + r(t) \tag{8}$$

An impact signal and its IMF is shown in Fig. 3

Based on the frequency dispersion characteristic of impact signal, EMD is applied to decompose the detected signal to several IMF, one of which is then selected to be the research object instead of the original signal. In consideration of mode aliasing, wavelet analysis is chosen to refine the selected IMF so as to get an IMF with purer content of frequency.

2.3 Denoise using Discrete Wavelet Transform

As a time-frequency analysis method, wavelet transform is capable to cope with the signals under multiple resolutions. It transforms a signal into several sub-signals with different frequencies[8]. The components of high frequency can be filtered by denoising the sub-signals with different thresholds.

Wavelet transform calculate the integration of inner product of the square-intertribal function $x(t)$ and the mother wavelet $\psi(t)$ with displacement of τ

$$WT_x(a,\tau) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t)\psi^*(\frac{t-\tau}{a})dt \tag{9}$$

Here, a is the scale element and satisfy $a > 0$. The equivalent expression in frequency domain is

$$WT_x(a,\tau) = \frac{\sqrt{a}}{2\pi} \int_{-\infty}^{+\infty} X(\omega)\Psi^*(a\omega)e^{j\omega\tau}dt \tag{10}$$

Where $X(\omega), \Psi(\omega)$ is Fourier transform of $x(t), \psi(t)$ respectively. Wavelet transform gradually analyses the signal from general to detail in time domain and acts as a band-pass filter with multiple scale in frequency domain.

An appropriate mother wavelet is import to wavelet transform because the mother wavelet function is not unique and the result of wavelet transform differs while different mother wavelet function is used. Daubechies mother wavelet function is selected in this paper according to the rule of choosing a mother wavelet function and the feature of the IMF including exponential regression and amplitude oscillation etc.

After wavelet transform is applied to the signal, thresholds based on the magnitude of the noise for corresponding details are calculated to process the obtained wavelet coefficients.

As there might exist break at some point of the processed signal using hard threshold which set the wavelet coefficient less than the threshold to zero, the method of soft threshold makes the reconstructed signal relatively smooth by converging the incontinuous point to zero on the basis of hard threshold. Soft threshold denoising can be expressed as

$$WT_{i,j} = \begin{cases} \mathrm{sgn}(WT_{i,j})(\left|WT_{i,j}\right| - Th) & \left|WT_{i,j}\right| \geq Th \\ 0 & \left|WT_{i,j}\right| < Th \end{cases} \tag{11}$$

Here, $WT_{i,j}$ means the j th wavelet coefficient of the k th order and Th is the threshold.

Denoised signal is then obtained by applying inverse wavelet transform on the processed wavelet coefficients.

Time differences can be figured out by analyzing different IMF from different sensors and the corresponding propagation velocity can be estimated by dominant frequency, thickness and material properties of wave propagating medium which is a steel board in this paper.

3. Simulated experiment and data analysis

In the purpose of validating the proposed method, simulation experiment is designed. The results obtained by applying different method are compared.

3.1 Simulating experiment arrangement

Experiment for simulation of impact caused by loose parts on the wall of the reactor pressure vessel is performed on a steel board with the size of $5100 \times 2210 \times 35$ mm. Surface of the board is divided into many grids with the size of 300×300 mm. A steel ball weighted 510g is used to simulate the loose part. The impact signals are simulated by dropping the steel ball from a certain height to the steel board at the crossing points of lines. Impact signals are acquired by the synchronous data collecting card (FCFR-USB2066, 16Bit), the charge amplifiers and the acceleration sensors fixed on six positions on the board which is regarded as the expended wall of the pressure vessel. The scheme of the simulated experiment is shown as Fig 4.

IMF is obtained by decompose the detected signal using EMD. Considering the magnitude of the IMF amplitude and the dominant frequency peak purity of the signal, the 3rd IMF is chosen to be the research object according to the IMF of the data from all channels of the detected signal. DWT is then applied to denoise the chosen IMF to make its frequency peak purer so as to make further reduction of the effect of frequency dispersion and the position of the start point.

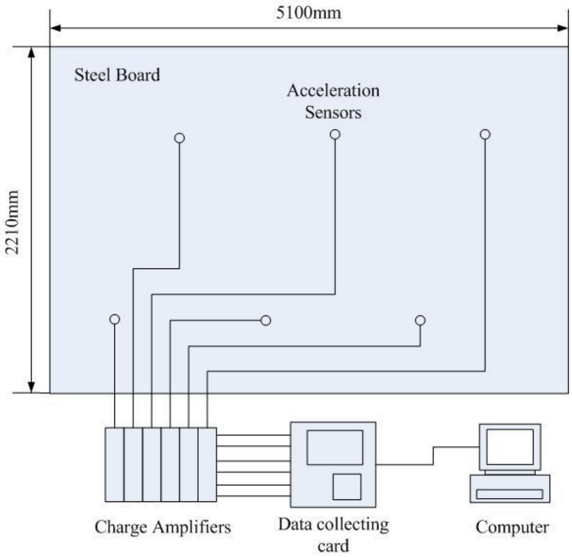

Fig.4 The scheme of the arrangement of the simulation experiment.

3.2 Start point and wave velocity calculation

The way to decide the start point of the vibration is the base of measuring the time differences of wave arrival. The popular methods are root mean square (RMS), cumulate and wavelet analysis[9]. RMS which is easy to use and relatively stable, is chose in this paper. RMS is calculated based on sectors with a certain length n of the time-series signal $x(t)$:

$$RMS = \sqrt{\frac{1}{n}\sum_{j=i}^{i+n}(x(j)-m)^2} \tag{12}$$

Here, i is the start point of RMS sector and m means the average of the sector. The threshold is defined by the practical experiment. Firstly the RMS of the background noise without impact signal is obtained as RMS_{noise}. Then the threshold for judging the start point of the vibration is calculated by multiplying RMS_{noise} with a constant coefficient obtained from experiment. Normally the value of threshold is within the range of 3-10. Process the signal with RMS, the start point can be defined once the acquired RMS is beyond the threshold.

The detected impact signal propagates in the medium with its group velocity. As the intrinsic mode of the original signal with part frequency of the original signal, IMF signal propagates with its group velocity too.

According to the structure vibration theory and the acoustic theory[10], the phase velocity of a signal can be expressed through equation (13) on the assumption of that the signal is harmonic wave and the board is infinite and free of constraints.

$$c_p = \frac{\omega}{k_b} = \omega^{0.5}\left(\frac{Eh^2}{12\rho(1-\upsilon^2)}\right)^{0.25} \tag{13}$$

Here, ω and k_b is the angular frequency and wave number of the bending wave, E, ρ and υ is the modulus of elasticity, density and Poisson ratio of the wave propagating medium respectively, h is the thickness of the steel board. Then the group velocity CG of the bending wave with a dominant frequency of WM can be acquired by making use of the relation between the phase velocity and the group velocity.

$$c_g = 2c_p = 2\omega_m^{0.5}\left(\frac{Eh^2}{12\rho(1-\upsilon^2)}\right)^{0.25} \tag{14}$$

Where ω_m represents the dominant angular frequency of the signal. From equation (14), the group velocity is obtained.

3.3 Experiment data analysis

Velocity of a bending wave can be determined by the material coefficient of the steel board, the thickness of the steel board and the domain frequency of the chosen IMF of the signal. The start point of a vibration can be obtained from the wave form of the given IMF in time-domain. Time differences of vibration arrivals detected by different sensors are then figured out by the start points and the sampling rate. The impact position of the loose part can be estimated by using triangular locating method for processing the wave velocities and the time differences.

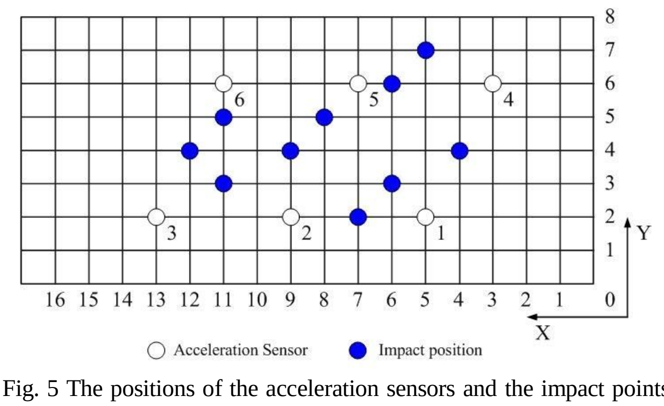

Fig. 5 The positions of the acceleration sensors and the impact points on the board.

NO.	Real Position (cm)	Calculated Position (cm)	Wave Velocity (m/s)	Relative Error (cm)
1	(120, 120)	(134.19, 123.04)	1806.81	11.14
2	(150, 210)	(152.79, 195.05)	1806.81	15.21
3	(180, 90)	(172.51, 81.62)	1806.81	16.41
4	(180, 180)	(164.29, 175.26)	1931.56	13.56
5	(150, 210)	(152.79, 195.05)	1806.81	11.24
6	(240, 150)	(229.86, 136.52)	1806.81	14.51
7	(270, 120)	(263.39, 128.43)	2159.60	10.70
8	(330, 90)	(319.43, 81.51)	1806.81	17.25
9	(330, 150)	(328.27, 158.11)	1931.56	8.29
10	(360, 120)	(345.25, 111.05)	1806.81	16.87
		Average	1867.04	13.52

Table. 1 The results of the locatings by using the proposed method.

The simulated impacts are carried out at the crossing points of the grids. Data detected on 10 of the all positions are processed to locate the position. The chosen positions are represented by the corresponding circles on Fig. 5. The real position coordinates, calculated positions, estimated wave velocities and relative errors of distances between the real and estimated positions are listed in Table.1. Table. 1 shows that the maximum relative error of locating the impact position using the proposed method is 17.25cm, the minimum relative error is 8.29cm and the average relative error is 13.52cm. The average relative errors of calculating the estimated positions using the proposed method and by the traditional methods (RMS and Cumulate method) are recorded in Table. 2. It is obvious that the proposed method has a better result. It proves that the proposed method based on EMD and DWT is feasible and reliable.

No.	*Name of Method*	*Average Relative Error (cm)*
1	Proposed Method	13.52
2	RMS	17.56
3	Cumulate	18.08

Table. 2 Comparison of the average relative errors among different locating methods.

4. Conclusions

Aimed at the difficulty in determining the start point of a complex vibration signal, a new method using EMD and DWT is proposed in this paper. EMD is utilized to decompose the time-series signal into a collection of IMF which have a relatively pure frequency distribution. With a proper wavelet basis function, DWT is then used to purify the chosen IMF so as to calculate the corresponding wave velocity and the time point at which the wave starts. This method changes complex signal with frequency dispersion into a component with sole peak in frequency domain. The velocity of wave propagation is calculated but not measured in this paper and thus the error caused by wave velocity measurement is avoided. Comparison of the results from the simulated experiment by proposed method and the traditional methods shows that locating errors of the proposed method are relatively smaller. Therefore, the new method is proved to be feasible.

REFERENCES

1 B.J. Olma, Source location and mass estimation in loose parts monitoring of LWR[J], Progress in Nuclear Energy,1985,15:583-593

2 Y.B. Kim, S.J. Kim, H.D. Chung, A study on technique to estimate impact location of loose part using Wigner-Ville distribution[J], Progress in Nuclear Energy, 2003, 43(1-4):261-266.

3 J.H. Park, Y.H. Kim, Impact source localization on an elastic plate in a noisy environment[J], Measurement Science and Technology, 2006,17: 2757-2766.

4 J.H. Park, Y.H. Kim, Impact source localization on an elastic plate in a noisy environment[J], Measurement Science and Technology, 2006,17: 2757-2766.

5 S.N. Jeong, K.H. Woo, E.T. Hwang, A study on the estimation method of impact position using the frequency analysis, IFOST2007, 2006:392-395.

6 Huang N. E. The empirical mode decomposition and the Hilbert Spectrum for nonlinear and non-stationary time series analysis[J]. J. Proc. R. Soc. Lond. A, 1998, 454: 903-995.

7 Huang Chengti. Study on Hilbert-Huang transform and its application[D]. Southwest Jiaotong University Master Degree Thesis, 2006.

8 Guo D F · A Study of Wavelet Thresholding De-Noising [C] · In: IEEE Proceeding of ICSP, 2000:329-332.

9 S.M. Ziola, M.R. Gorman, Source location in thin plates using cross-correlation[J], Journal of the Acoustical Society of America,1991,90:2551-2556.

10 Cremer L, Heckl M, Ungar E. Structure-borne sound[M]. 2nd ed. Berlin: Springer-Verlag,1998