A Modified Synthetic Aperture Focusing Technique (SAFT) by the Hilbert-Huang Transform (HHT)

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Abstract

Combing the stress wave signals with Synthetic Aperture Focusing Technique (SAFT) to inspect and image the interior defect of concrete structural has shown its feasibility by some researchers. However, some bright zones displayed in the image plot are not corresponding to the Rayleigh waves and reflection signals from the bottom surface of the structural component or the embedded defect. This type of image is treated as a fictitious defect and will affect the judgment of nondestructive evaluation. Since the theorem of SAFT is based on the superposition of all the amplitudes of receiving signal at the flight time corresponding to each image cell in the domain of inspection, the irregular waveform in the time domain can generate the abovementioned fictitious defects. In this paper, the synthetic aperture focusing technique is modified by using the frequency, time and energy information from the Hilbert-Huang Transform (HHT) method to improve its image quality. It is found that the reflected signal from defect will be located in a certain band of frequency and the energy level at the time corresponding to a defect is relatively high. Numerical simulation results reveal this feature of HHT method can filter out the fictitious image displayed in the previous method and provides a clearer and sharper image of real defect.

Keywords: SAFT, HHT, image, defect, frequency, stress wave

1. Introduction

Among the present nondestructive testing (NDT) technologies for civil engineering, the elastic-wave based techniques play a very important role. The point-source/ point-receiver scheme is especially suitable for the inspection of on-site civil infrastructures. Chang *et al.* [1] and Liu *et al.* [2] used the imaging technique to display the tip of surface- breaking cracks in reinforced concrete. The impact-echo method, which transforms the time-domain signal into the frequency domain one, then searches for the resonance frequency, to back-calculate the defects inside a specimen [3-4]. By combing the stress wave signals in time domain with Synthetic Aperture Focusing Technique (SAFT), the image of interior defect of concrete structural can be obtained [5-7]. In the SAFT theory, the small variance of the signal amplitude will affect the image fidelity by adding some unnecessary bright zones. Other factors like the compositions of material and geometrical boundaries may also add unnecessary bright zones as fictitious defects. In order to get much better image, this paper proposes a technique to transform the signals in time domain to domains of instantaneous frequency as function of time by the Hilbert-Huang Transform (HHT) method [8-9] to conduct analysis by the SAFT. Numerical simulation signals were used to verify the feasibility of the proposed technique.

2. SAFT Theory

A point-source/ point receiver measurement scheme as shown in Fig. 1 is used to scan over the top surface of a structural component with interior defects. A series of time domain signals are measured. Let S_i and R_i represent the locations of a set of the source and receiver for the *i*-th measurement. Furthermore, let $T_i(t)$ be the magnitude of the response signal recorded at R_i for this measurement. The domain of the specimen then is meshed by cells. An image intensity $I(m, n)$ can be assigned to cell with an address code (m, n) based on the following calculation:

$$I(m,n) = \frac{1}{N}\sum_{i=1}^{N} T_i(t_i) \tag{1}$$

$$t_i = \frac{\left|\overrightarrow{S_i I}\right| + \left|\overrightarrow{IR_i}\right|}{V_P} \tag{2}$$

where m and n specify as the spatial address code of a image cell, N is the total number of the measuring signals, and V_P is the propagating speed of the longitudinal stress wave. According to the elastic-wave theory, the wave will be reflected at the interface of two media with different acoustic impedances. The reflection can be found in the response time history if it can be sensed by the transducer. In the general case, however, there are so many reflected signals from the boundaries and defects of the object to be inspected. The determination of the location of a defect from the complex trace sometime is not an easy work. Besides, the dimension of the defect cannot be obtained from a single response signal. In the SAFT-imaging process, the geometric information of a defect can be recovered not only from one set of the response signals but also from all of them. The image intensity I corresponding to each mesh cell is determined by summing the amplitudes of all the measured signals at the corresponding time t_i, then taking an average value. The time t_i is taken as the theoretical traveling time for the longitudinal wave to propagate from the impacting source to the target cell, and then it travels back to the receiver. In this paper, two levels of darkness are used to achieve a better contrast of image, high-image density values associated with defects and interfaces will be displayed with dark black, and low density values associated with uniform matrix will be displayed with bright white.

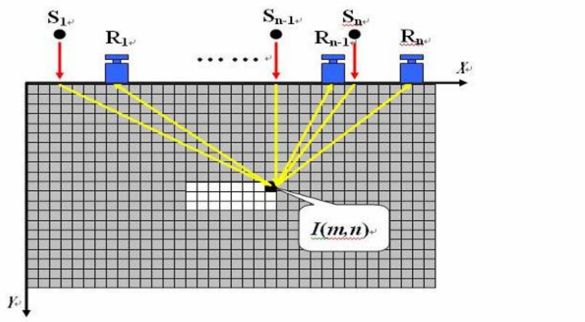

Figure 1. Implementation of impact-and-receive operations and meshing of specimen for the image construction by SAFT.

3. Image Improvement on SAFT by the HHT

Over the past few years, an adaptive data analysis method called as the Hilbert-Huang Transform (HHT) [8-9] has been developed to determine the instantaneous frequency precisely. This wonderful ability of HHT has been utilized by researchers in various fields and many impressive results have been obtained. The HHT approach is based on the decomposition of any given data adaptively into simple oscillatory function designated as Intrinsic Mode Functions (IMF) satisfying the following conditions: (a) in the whole data set, the number of extrema and the number of zero-crossings must either equal or differ at most by one, and (b) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. An IMF represents a simple oscillatory mode as a counter part to the simple harmonic function, but it is much more general: instead of constant amplitude and frequency in a simple harmonic component, IMF can have variable amplitude and frequency as functions of time. HHT can clearly define nonlinear deformed waveforms trough instantaneous frequency variation as function of time. The receiving waveforms will be distorted at the time of reflecting from interface, which give intra-wave frequency modulation. The consequence is a broadening of the marginal Hilbert spectrum. Hence, we can use the variation of the instantaneous frequency as a clear indication of reflection. This motivates us to do the image improvement on SAFT by the HHT method.

A typical time domain signal as shown in Fig. 2, one can identify those possible positions of the reflection wave of defect as the peak with duration Δt . We can approximate this wave peak by a half sine function and use Eq. (3) to calculate the corresponding frequency.

$$f_c = \frac{1}{2 \times \Delta t} \tag{3}$$

This frequency is called as the center frequency of the reflective wave at defect and will be used in the analysis by HHT. After transforming the signals by HHT, the relationships among the time, frequency and energy as shown in Fig.3 can be obtained. The time varying energy for the frequency band characterized by the center frequency is then further used as the response signal $T_i(t)$ in the SAFT theory. According to stress wave theory, the frequency energy will have abrupt change at the interface. However, some error may be generated in calculating center frequency. In order to remove the error effect, a frequency band is made by the center frequency f_c and a band width $2\Delta f$. This frequency band is used as a window to observe the arrival time of the wave to the reflection interface.

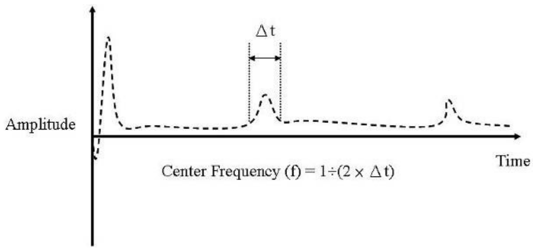

Figure 2. A typical signal in time domain.

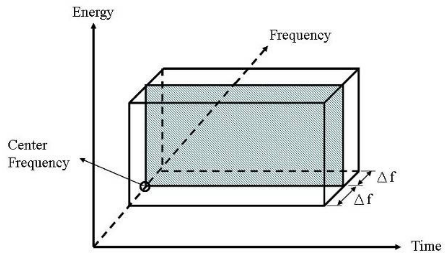

Figure 3. Relationship among time, frequency and energy of a signal after HHT.

4. Image of Embedded Defect by the Modified SAFT

To verify the feasibility of using the instantaneous frequency variation function to improve the image quality of the SAFT, a set of inspection signals on a concrete block with defect are generated numerically by a finite element code. As shown in Fig. 4, this rectangular concrete block has a dimension of 2m x 1m and a void defect of 0.2m x 0.1m is 0.45 m under the top surface of the block. The distance between the right sides of the void and the matrix is 0.8 m. The Lame constant, λ, μ, and mass density of the concrete block are *6.890×109 N/m2, 1.379×1010 N/m2,* and *2300 kg/m*^{3}*,* respectively. Therefore, the longitudinal wave speed is 3871 m/s. A series of impact-and-receive operations then is performed on the top surface of the block, as indicated by $\{S_1, R_1\} \ldots \{S_i, R_i\}$, etc. on Fig.1. The impact force is assumed to be generated by dropping a steel ball of 6 mm in diameter. The force history is approximated by a half sine function of $\sin^{3/2} t$ with contact duration of *30 μs*. The response signals of the displacement and velocity are outputted for the feasibility analysis. The first impact site *S*1 is applied at *0.7 m* from the left side of the block. The distance between the source point and the receiver is fixed as *0.05 m*. After the response is measured, the impacting source is moved *0.025 m* to the right for the next measurement. Fig. 5 shows the B-scan diagram of the 25 vertical displacement signals. The peak at *250μs* is used to calculate the center frequency of the frequency band. Figure 6 shows the image plot by the conventional SAFT using time domain signal. The black zone marked by a rectangular grid in Fig.6 is the defect inside concrete structure. But in addition to black zone of defect, some light darkness zone appeared around the defect that my affect the evaluation result of the exact size and location of the defect.

Shown in Fig.7 is the B-scan diagram of the 25 time varying energy signals in a frequency band from the HHT analysis. Figure 8 is the SAFT image generated from energy responses and the light darkness zone in Fig. 6 had be removed so that the black zone of defect becomes more clearly and its position is more easily identified.

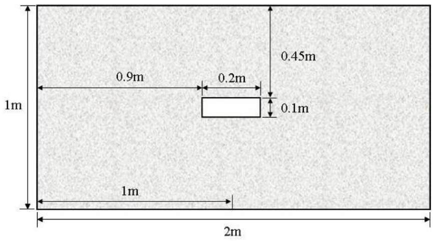

Figure 4. Dimensions of concrete specimen with a single rectangular shaped void defect.

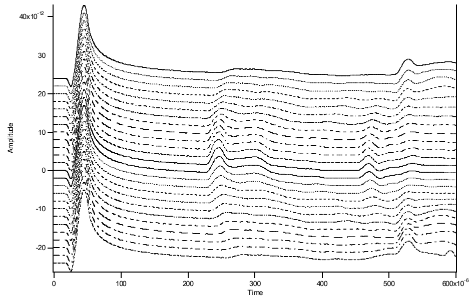

Figure 5. B-scan diagram of the measured signals in time domain of a concrete specimen with single rectangular defect.

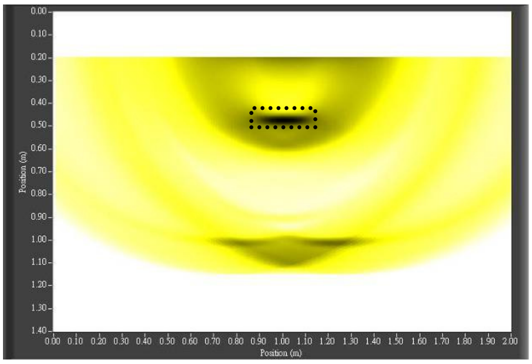

Figure 6. A SAFT image generated from time domain signals.

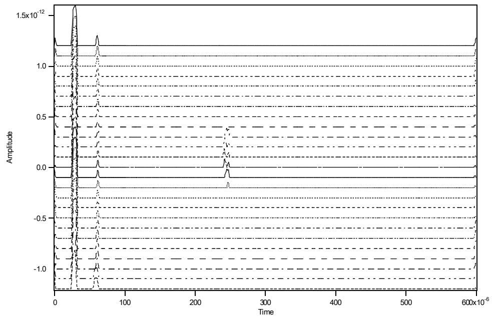

Figure 7. B-scan diagram of the energy-time relations of a concrete specimen with single rectangular defect within a frequency band of center frequency *12.5KHz* and half bandwidth Δf equal to *2KHz*.

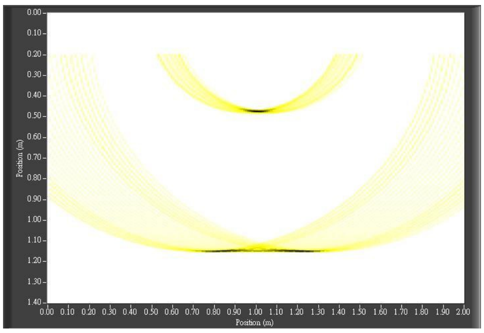

Figure 8. A SAFT image generated from responses of frequency energy varying in time.

5. Conclusions

A modified synthetic aperture focusing technique by Hilbert-Huang transform is proposed in this paper. The instantaneous frequency variation as function of time is more sensitive to the existence of defect. If we observe and analyze the signal by SAFT within a frequency band, a clearer image plot can be generated. This modified method can remove unnecessary signals but also filter out some other signals. Hence, the fidelity of the defect shape is low. Although the defect shape can not be identified only from the SAFT image in frequency domain but it can get more information from the B-scan diagram of energy variation as function of time. Therefore, it is suggested that the shape and location evaluation process of defect must combine the B-scan diagram of energy –time variations and the SAFT image plot. In the future, experimental verification on this modified SAFT will be conducted.

6. References

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