Research on Ultrasonic Detection of Air Spring Rubber Debonding based on CEEMDAN

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Abstract. The SYS510e air spring of electric multiple unit (EMU) is the metal and rubber bonding structure. In order to carry out ultrasonic debonding detection on the tapered bonding interface, after correcting the interference caused by sectional thickness change, the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) and cross approximate entropy (ApEn) method was applied to analyze time frequency characteristics of echo under different bonding conditions. Five numbers of cross ApEn features were extracted to identify rubber debonding defect. These features are more stable and show more significant discrepancies between bonding and debonding states. Then BP neural network was trained to identify the debonding state of the tapered interface of air spring. The results of ultrasonic C scan show that the ultrasonic detecting method based on CEEMDAN and cross ApEn can accurately and effectively identify the location and contour of rubber debonding defects, and meet the needs of the debonding detection of SYS510e air spring of EMU.

1. Introduction
As the second suspension of bogie’s suspension system of EMU, air spring has the functions of supporting train’s body and buffering impact. It is often impacted by complex dynamic loads during EMU operation. The inner metal and rubber’s bonding structure is prone to produce rubber debonding defect, which affect the performance of air spring and threaten the safety of EMU operation [1]. At present, the railway bureau carries out regular maintenance of air spring through visual inspection and knocking manually, which lacks effective detection means for the internal rubber bonding states.

Ultrasonic detecting is a widely used non-destructive testing method. In recent years, it has been applied to the debonding detection of metal and rubber’s bonding structures in the fields of rocket and automobile applications [2, 3]. Its basic principle is to analyze and compare the difference of energy attenuation of the echoes, which are reflected from a dielectric interface with different acoustic impedance. And the higher the echo’s order is, the more obvious the difference of energy attenuation between the debonding and bonding states is. Therefore, the acoustic pressure ratio of high-order echo is often used as the feature to identify the state of rubber’s debonding or bonding. The method is effective for thin and uniform thickness mental-rubber bonding structures. However, for the SYS510e air spring of EMU, the metal-rubber bonding structure of the base is the tapered metal with uneven thickness as shown in Fig.1. There is an angle between the incidence and reflection of the ultrasonic
wave. The echo propagates far away after several reflections between the upper and lower interfaces of the metallic layer. When using a single probe to send and receive ultrasonic waves, the echo order of ultrasonic waves that can be received is very small. So it is impossible to identify the debonding state by using the characteristics of acoustic pressure ratio of high-order echo. Moreover, with the change of the thickness of metallic layer of the base, the position of the echo on different sections changes (the abscissa of the A-type display). The change of thickness makes the ultrasonic transiting time and energy attenuation also change. Therefore, it is more difficult to detect and identify the rubber debonding defect of SYS510e air spring.

The paper proposed to compensate thickness of ultrasonic echo of tapered structure. Then the CEEMDAN method was used to extract a series of intrinsic mode functions (IMF) after thickness compensation [4]. According to the correlation of IMF with original ultrasonic signal, the cross ApEn was extracted from the IMF.

Compared with the traditional method of ultrasonic echo energy attenuation, the proposed method reduces the interference of thickness by compensating. CEEMDAN and cross ApEn can further reduce signal noise and extract distinct and stable features. It enhances the accuracy and stability of ultrasonic detection.

2. Structure of Air Spring
The SYS510e air spring of the EMU is composed of upper cover, rubber bladder, lower cover, auxiliary spring, and base, etc. [5] The structural and physical diagram are shown in Fig. 1 and Fig. 2. The rubber debonding defect often occur on the interface between the tapered metal of base and the auxiliary rubber pile. The maximum radius \( r \) of base is 180mm. The thickest metal is 20mm, and the thinnest metal is 10mm. The projection length of one-sided inclined bonding plane is 110mm. The inclined angle is about 5 °. Vulcanized rubber uniformly covers the whole inclined plane of base. The rubber of air spring was cut artificially to set the area of rubber fully debonding for ultrasonic testing and comparing convenience. The chirp pulse was used to excite a small angle ultrasonic inclining probe (the refracting angle 5 °). The air spring was detected by the ultrasonic echo method with only one probe sending and receiving. According to the thinnest mental of the base (10mm), set the center frequency of the chirp pulse \( f_0 = 2.5 \text{MHz} \), time width \( t = 4 \mu \text{s} \), and bandwidth \( B = 5 \text{MHz} \). The echo signal is shown in Fig. 3.

![Fig. 1 Structure diagram of SYS510e air spring](image-url)
3. Thickness Compensation of Echo Signal

The echoes’ comparison shows that under the same thickness, the echoes’ energy attenuation of rubber debonding state is smaller than that of bonding state, and three orders of echoes can be obtained (Fig. 3). The interference of echoes’ sidelobe is smaller and the regularity is stronger. As the metallic thickness increases, the transiting time and energy attenuation of the echoes increase continuously. The factor of thickness interferes with the identification of the rubber debonding defect.

In order to accurately obtain the ultrasonic echo features reflecting the rubber debonding defect, the paper performed thickness compensation on the ultrasonic echoes. All echoes are unified to the same thickness of 10mm to eliminate the interference of variable thickness. The compensatory method is listed as follows. The compensatory diagram is shown in Fig. 4.

a) According to the ultrasonic attenuation equation (1) [6], the attenuation curve of ultrasonic echo in the state of rubber debonding and with 10mm thickness is established as the compensatory reference of attenuation. Its coefficient is $P_0 = 1.549$, $\alpha = 1.625$.

$$P_x = P_0 e^{-\alpha x} \quad (1)$$

Where, $x$ is the distance between the current ultrasonic echo and the sound source. $\alpha$ is the ultrasonic attenuation coefficient. $P_0$ is the initial sound pressure.

b) The echo’s transiting time $t$ of 10mm thickness is about 0.52$\mu$s. By windowing and truncation of echoes, multiple peaks $P_1$, $P_2$, $P_3$ and correspondent positions $x_1$, $x_2$, $x_3$ are extracted. Then splicing data to unify transiting time.
c) According to the 10mm thickness attenuation curve of rubber debonding state, substituting the positions $x_1$, $x_2$, $x_3$ of the ultrasonic echo, the compensation formulas of peak’s energy attenuation are expressed as:

\[
P_{\text{in}} = 1.549 \times 10^{-1.625x_i}
\]

(2)

\[
B_i = P_i + P_{\text{in}}
\]

(3)

\[
P_{\text{Bi}} = P_{\text{in}} \times B_i
\]

(4)

Where, $i$ is the order of ultrasonic echoes. $P_{\text{in}}$ is the peak of the $i_{th}$ order echo to be compensated. $P_i$ is the peak of the $i_{th}$ order echo of the compensatory reference. $B_i$ is the peak’s compensatory factor. $P_{\text{Bi}}$ is the peak after compensation.

Theoretically, the slope of the ultrasonic attenuation curve of the bonding state is larger than that of the debonding state at the same thickness Therefore, using the attenuation curve of debonding state not only will not change the corresponding characteristics of the echoes of rubber bonding state, but also correct the energy attenuation caused by different thickness.

![Thickness compensation of ultrasonic echoes](image)

**Fig.4** Thickness compensation of ultrasonic echoes

4. Extracting Debonding features

It is difficult to directly judge the rubber debonding defect by the energy attenuation of echoes in the ultrasonic detection of sys510e air spring. Therefore, time-frequency characteristics of echoes were analyzed. By comparing the difference of multi-segment signals obtained by the CEEMDAN decomposition, the identifiable features reflecting the difference between the rubber bonding and rubber debonding were extracted.

4.1. CEEMDAN Decomposition

CEEMDAN decomposition is a time-frequency analytical method for nonlinear and non-stationary processes, which can obtain the complete energy-frequency-time distribution of the echoes. The core of the algorithm is to adaptively add multi-segment white noises based on the basic empirical mode decomposition (EMD), so that the decomposed data has scale continuity. Compared with the traditional time-frequency decomposed method, CEEMDAN decomposition has good noisy reduction and avoids modal aliasing. The decomposed algorithm is shown as follows \[^7\].

a) Add multi-segment white noises $n(t)$ to the original signal $X(t)$.
Perform EMD decomposition on $X_i(t)$ to get $\text{imf}_{11}$, calculate CEEMDAN’s $\text{IMF}_1(t)$ and the first residual $r_1(t)$. 

\[
\text{IMF}_1(t) = \frac{1}{N} \sum_{i=1}^{N} \text{imf}_{11} = \text{imf}_{11}
\]  

\[
r_1(t) = X(t) - \text{IMF}_1(t)
\]  

Taking the first residual $r_1(t)$ as the new target signal. Add noise to $r_1(t)$ and perform EMD decomposition to get $\text{imf}_{21}$, calculate CEEMDAN’s $\text{IMF}_2(t)$ and the second residual $r_2(t)$. The process is repeated $k$ times until the residual can not be decomposed.

\[
\text{IMF}_k(t) = \frac{1}{N} \sum_{i=1}^{N} \text{imf}_{21}
\]  

\[
r_k(t) = r_{k-1}(t) - \text{IMF}_k(t) \quad k = 2, 3, ..., K
\]  

d) Finally the original data $X(t)$ can be expressed as:

\[
X(t) = \sum_{i=1}^{K} \text{IMF}_i(t) + r_k(t)
\]  

The thickness-compensated ultrasonic echo is decomposed into 9-stage IMF by CEEMDAN decomposition. The result is shown in Fig. 5.
Comparing CEEMDAN decomposition results of two kinds of bonding states, ultrasonic echoes have more instantaneous frequency information in all stages of IMF. Its main components are concentrated between IMF \(1\) and IMF \(5\). And the IMF of the rubber debonding state has stronger regularity and smaller noise, which show more obvious signal difference. The cross ApEn between the first 5 numbers of IMF and the original echo (after thickness compensation) of 10mm mental thickness with rubber debonding. The cross ApEn is used as the rubber debonding identifiable feature, which has excellent accuracy and reliability.

4.2. Cross ApEn

The cross ApEn is a nonlinear non-negative kinetic parameter that represents the temporal regularity and difference between signals. It reflects the probability of recurring between data and it is unique. Theoretically, the larger the cross ApEn, the worse the repetitive probability of the two signals and the more significant the difference of the waveform [8].

a) Set the dimension of algorithm \(M\) and the tolerance threshold \(p\). Make \(\text{IMF}_k(i), i = 1, 2, \ldots, n\) and the 10mm thickness debonding echo \(v_b(j), j = 1, 2, \ldots, n\) into \(M\)-dimensional data vector.

\[
W_k(i) = [\text{IMF}_k(i), \text{IMF}_k(i + 1), \ldots, \text{IMF}_k(i + M - 1)] \quad 1 = 1 \sim n - M + 1, \quad k = 1 \sim 5
\]

\[
V(j) = [v_b(j), v_b(j + 1), \ldots, v_b(j + M - 1)] \quad j = 1 \sim n - M + 1
\]

b) Calculate the maximum difference \(D\).

\[
D = \max\left[ | W_k(i) - V(j) | \right]
\]

c) Calculate the distance ratio \(c^M(p)\) and the degree of correlation \(\theta^M(p)\) corresponding to each \(i\) value.
The cross ApEn is expressed as.

\[
C_1^M(p) = \frac{1}{n-M+1} \left[ \sum_{D \leq p} \text{number} \right]
\]

(14)

\[
\Phi^M(p) = \frac{1}{n-M+1} \sum_{i=1}^{n-M+1} \ln C_1^M(p)
\]

(15)

d) The cross ApEn is expressed as.

\[
Y(M, p) = \Phi^M(p) - \Phi^{M+1}(p)
\]

(16)

Setting \(M=2\), \(p=0.2\sigma\). \(\sigma\) is the standard deviation between the IMF\(_k\)(i) and \(v_0(i)\). The 50 numbers of sets of ultrasonic echoes were acquired for five different bevel thickness positions under rubber debonding and rubber bonding states, respectively. The total sets of echoes are 500. The debonding identifiable features of the conventional acoustic pressure ratio-ratio of the first-order echo to the second-order echo are shown in Fig. 6. The debonding identifiable features of the CEEMDAN-cross ApEn are shown in Fig. 7.

Fig. 6 Conventional acoustic pressure ratio of 500 sets of data

Comparing Fig. 6 with Fig. 7. The traditional method of extracting acoustic pressure ratio is only suitable for the situation where the thickness is equal and the energy attenuation is small, and the number of echoes is large. But for the ultrasonic detection with changing thickness, the traditional method is difficult to accurately and reliably identify rubber debonding defect. However, the CEEMDAN-cross ApEn method after thickness compensation is based on the echoes’ regular differences of multiple time-frequency IMFs. It can extract relatively stable cross ApEn as identifiable features and has significant difference.
5. Ultrasonic C scan experiment

Using the extracted cross ApEn features, the BP neural network with 3 layers and 11 hidden units was trained. The SYS510e air spring was subjected to ultrasonic C-scan detection. The angle of sector area is 60°, and there is an artificial rubber debonding area with an angle of 24°. According to the diameter of the probe (2.5P20 5°) 20mm, divided the scanned area into a 5-layers incremental network. The outermost layer has 16 numbers of grids. The single mesh size is approximately 22mm × 10mm rectangle, and the step of scanning movement is 10mm. The scanned mesh diagram is shown in Fig. 8.

![Fig. 8 Ultrasonic C-scan detected schematic](image)

Ultrasonic C-scan used the BP neural network output as the intensity to identify whether rubber debonding or not. The detection and identification were performed point by point. The corresponding intensity matrix with 5 layers and total 60 points was obtained. The intensity of 100 indicates debonding, and the intensity of 0 indicates bonding. Due to the restriction of numbers of training samples and the difference of coupling conditions, the intensities of some detected points are between 0 and 100, and there is an uncertainty. By interpolating the intensity matrix, the ultrasonic C-scan is shown in Fig. 9.

![Fig. 9 The ultrasonic C-scan result of SYS510e air spring with artificial rubber debonding defect](image)

Comparing the ultrasonic C-scan result with the actual rubber debonding defect size, the thickness-compensated CEEMDAN-cross ApEn method is effective. The debonding defect of the tapered metal
of the SYS510e air spring can be accurately detected and identified. The method has a higher detectable accuracy and reliability.

But the effect of ultrasonic debonding detection is affected by the roughness of the detected interface. The metallic surface of the SYS510e air spring is coated with paint. Due to the long-term operation of the EMU, paint peeling and metal scratches on the bottom plate often take place. Therefore, when ultrasonic scanning is performed with large superficial roughness and poor coupling, the detected echo may be contaminated.

6. Conclusion
For the ultrasonic debonding detection of the tapered metal of rubber’s bonding structure of the SYS510e air spring, based on the thickness compensation the characteristic extraction with CEEMDAN-cross ApEn method were performed and analyzed. Compared with the conventional acoustic pressure ratio method, the proposed method can obtain identifiable features with more significant differences, more stability and better consistency. Carrying out ultrasonic C-scan on the bottom plate of air spring, the identification results of the trained BP neural network show that the proposed method is effective and can meet the needs of practical engineering.

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