Experimental Study on AE Energy Attenuation in Steel Cables

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Abstract

Acoustic emission (AE) is a phenomenon of strain energy releasing when a material undergoes deformation or crack. By collecting AE stress wave in cable surface continuously, the damage occur within cables will be monitored. This paper carries out experiments in cables to study the changing of stress wave propagating from center wires to edge wires, and from edge wires to PE surface. The energy attenuation laws also are analyzed with difference tension force. The results illustrate that, after the stress wave propagates in cables with a long distance, it will distribute in whole section evenly. The waveform amplitude attenuates clearly when it through PE layer, but the main spectrum feature is invariable. The energy attenuation laws measured in PE surface conforms to exponent model, and it affects by tension force obviously. However, after the cable is tensioned to a certain degree of cable yield force, the attenuation factor will not decrease with the tension force increasing.

Keywords

Health monitoring, Acoustic emission (AE), Steel cable, Energy attenuation, Wave propagation

Introduction

Cables are the main strengthening component in cable-supported bridge. A large amount of stay cables and suspenders had been damaged in early stage which suffering corrosion and fatigue stress in real bridge. Guangzhou Haiyin Bridge was opened to traffic in 1998 and the number 15 cable broke from south tower in 1995. Moreover, it was found that the number 9 cable was also loose and most of cables within 3 meters from tower top were corroded found in subsequent inspection, and then exchanged whole bridge cables. A short suspender in Nanmen Bridge broke off in 2001, and resulted in part of bridge deck collapse. It was found from field investigation that the steel strand corroded area is more than two-thirds[1]. Because the stay cables constructed in the end of last century will soon to its service life, it is urgent to carry out studies on cable damage monitoring to ensure the cables safely[2]. Another more realistic question is that the wires corrosion is a usual phenomenon in early stage of bridge service time, In generally, after eliminating the corrosion inducement and preventing corrosion became more deepen, the cable can be continue used with slight corrosion. However, the use of slight corrosion cables should be bases on effective real time monitoring.

At present, the methods for bridge cables monitoring is insufficient, the effective of what are the cable force monitoring based on vibration frequency and the AE method. Cables force can reflect its secure state in a certain extent, but the damage within cables can't be directly recognized by the changing of cable force. AE is a monitoring method with the characteristics of real time, passiveness, dynamic and nondestructive. Moreover, the measured signals relevant to damage directly and not affect by cable layer. Studies on damage monitoring have been carried out in steel wire rope and steel strand by AE since 1970s. Because of insufficient performance of acquisition card, the research results far cry from real bridge applying. Recently, along with the fast-developing of computer and acquisition card performance, the signal processing technology more and more base on full-waveform.

This paper introduces the fundamentals and research status of AE technology, and then carries out experimental studies on wave propagation characteristics in damaged cable, which contain the changing when wave across cable layer and wave distribution laws in that cross section far away from damage source, and the energy attenuation in propagation process. The work in this paper provides a foundation for damage monitoring in which the monitoring position is far away from damage source.

AE Technology and Advances

AE is a phenomenon of strain energy releasing when a material undergoes deformation or crack. Damages are the results of strain energy accumulation and release. Through monitoring the strain energy by sensors deployed in cable layer, the damage will be recognized by analyzing such measured full waveform.

Frequency bands of AE wave is very widely, usually layer the infrasonic frequency, audio frequency, and ultrasonic frequency. If the AE with enough energy, it will be heard by people's ears. Otherwise, Sensitive electronic equipment is necessary. Typical AE signal is shown as fig.1.

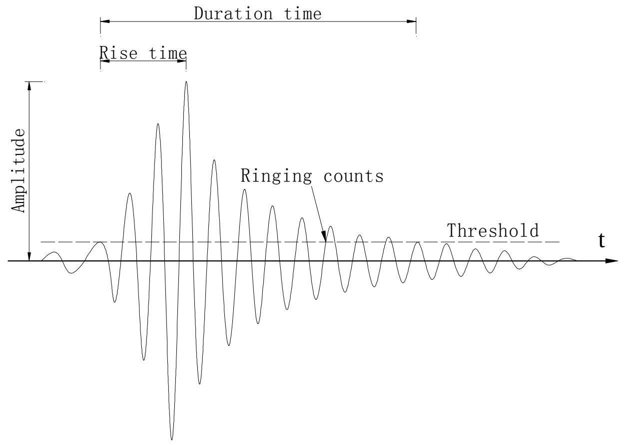


Fig.1 Typical AE waveform

The key technology for AE monitoring is to process of measured data, which is aim to confirm damage features, such as occurring time, position, type and degree. Now, the methods for data acquisition and processing are parameters analysis and waveform analysis. Although the parameters analysis is not suitable for monitoring successional damage, in most case, it has been verified that it is useful to solve the practical engineering problems[3].

Corrosion is one of the common damages in bridge cable, and it also the primary inducement of cable breakage. Many researchers have adopted AE method to study the process of corrosion. H.Idrissi etc.[4]adopted AE method to monitoring the corrosion process of prestressed steel. The sulfate and chloride are used to make the steel corrosion faster. Through analyzing AE accumulative event over time, the corrosion process is divided into three stages as crack initiation (stage A), crack growth (stage B) and tendon failure (stage C). The three stages are shown in fig. 2 and S1 to S4 means four monitoring positions.

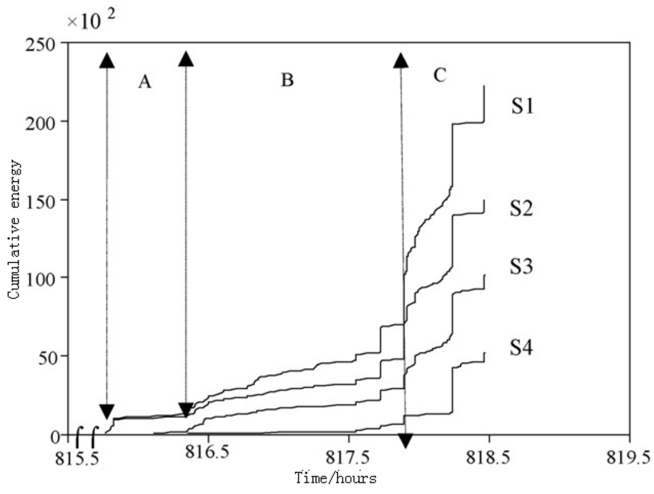


Fig.2 Energy accumulation curve in corrosion steel[4]

Lamine Djeddi[5], William Vélez[6], Jesé Mangual[7], Jinping Ou[8,9] have carried out corrosion experiments in cables to study AE parameters characteristic, and establish some warning model to evaluate the damage degree.

Fatigue is a catalyst in the process of corrosion deterioration. G. Drummond etc.[10] carry out fatigue experiment in cables, and study the relationship between fatigue process and parameters. The results illustrate that energy and amplitude are the most effective parameters, and the signal attenuation is not very serious, which can be detected 30 meters far away from damage position. T.M.Roberts etc.[11] establish the Eq.(2) to quantify the relationship between AE accumulated energy and stress intensity factor, which is similar to the existing Eq. (1) of crack growth rate.

$$\frac{\mathrm{d}a}{\mathrm{d}N} = \mathrm{C}_1(\Delta K)^{\mathrm{n}} \tag{1}$$

$$\frac{\mathrm{d}E}{\mathrm{d}N} = \mathrm{C}_2(\Delta K)^{m} \tag{2}$$

Where, a is crack length, N is the circulation number of fatigue, $\mathrm{d}a/dN$ is crack growth rate, E is accumulated energy of AE signal, C_1, C_2, n and m are decided by material, ΔK is the amplitude of stress intensity factor.

Dongsheng Li and H. Li[12,13]carry out fatigue experiments in carbon fiber reinforced polymer, and propose damage Indicator calculated by parameters to illustrate the cable fatigue stages.

After the cable deterioration induced by corrosion and fatigue, the consequences sometimes are wires breakage and the whole cable broken. Limin Sun etc.[14-16]carry out experiments in single wire and cables, and gain waveform characteristics of the wires breakage source. Lanza di Scalea F and Rizzo P[17-19]have carried out experimental and numerical study on cable damage recognize many years, in which the wavelet transform is a usual data process method.

Experimental and numerical study on AE monitoring in cables have been carried out widely, and some conclusions also are consistent. However, the study on damage extension laws that based on real cable experiments data, generally do not considering the difference between measured data and source data. In fact, cable length is not uniform in real bridge and the damage position can't be predicted, which will result in difference propagation distance for difference damage source. When the damage occurs far away from monitoring position, the stress wave propagates from source to sensors as shown in fig.3. It can be seen from fig.3 that the propagation process is essential to output signal, especially for that long distance propagation, which will make the experimental results difference from real bridge.

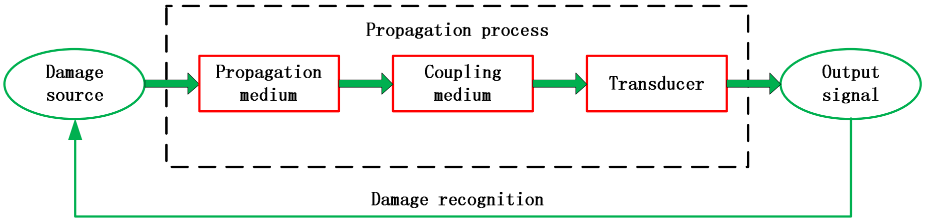


Fig.3 The whole process of AE monitoring

Experiment Method

The data acquisition system is PCI-2 produced by Physical Acoustic Corporation, and the sample frequency is 1MHz. Sensors' mid-frequency are 150 KHz, and it contact with cables by an elastic tape and the interface filled by couplant.

The experiments contains two conditions, one is carried out in a tension free cable shown in fig.4. The total length of this cable is 14.8 meters. Cable cross section contains 91 wires and 5 of which are prefabricated circular nick with 0.6 millimeter in depth (see fig.5). AE source is generated by high energy impaction, and the impact position is distributed at the center area of end section. Sensors layout are shown in fig.4.

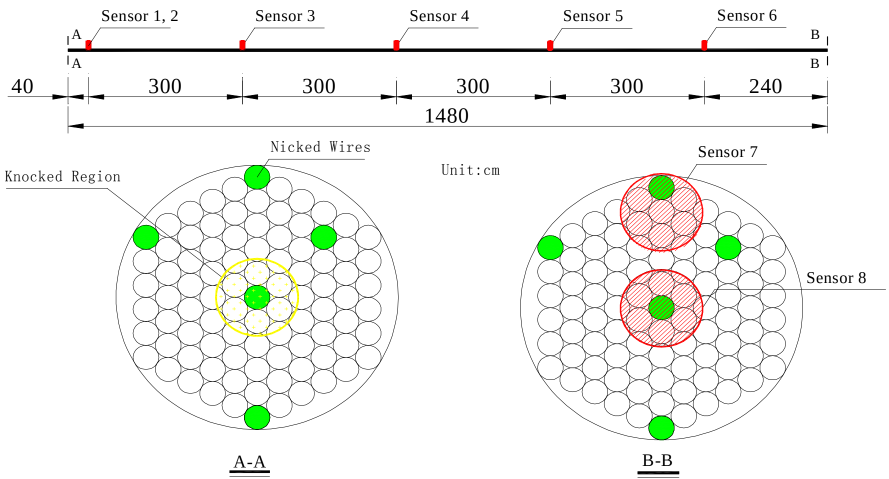


Fig.4 Experimental cables and sensors layout sketch

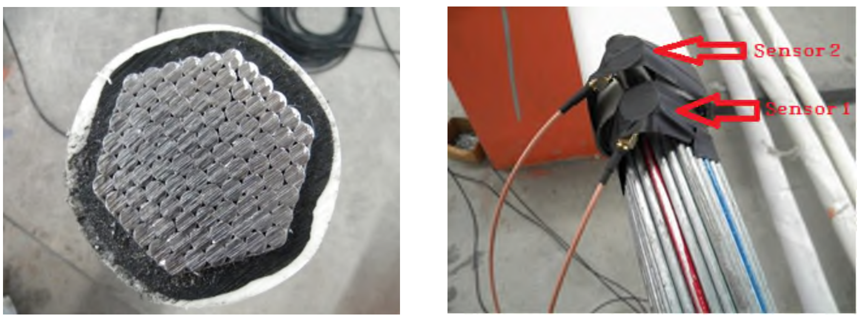


Fig. 5 Cable cross section and sensors layout

Another experiment is carried out in tensioned cable, which will snap several wires by step loading and the max tension force is 75 percents of the cable yield force (see fig.6). Five sensors, containing sensor2 to sensor6, are used to collected wire breakage signals in cables, and the sensor1, sensor7 and sensor8 are taken off after finish the first experiment condition.

Fig. 6 Cable stretch equipment and breakage wires

Analysis of Test Results

Whether the damages within cables can be identified depends on the changing of stress wave propagation from inner wires to PE surface. This process is divided into two parts, the first part is from center wires to edge wires, and the second part is from edge wires to PE surface, all of which are discuss in following.

Changing of Stress Wave From Edge Wires to PE Surface

In the first condition, sensor1 and sensor2 place at the same position in longitudinal direction, which difference is sensor1 at PE inside and sensor2 at PE surface (see fig.5). So, when the source generated from the center area of end section, the sensor1 and sensor2 pick up signals meanwhile. The acquisition data from sensor 1 and sensor 2 are shown in fig.7.

The waveform from two sensors present an obvious attenuation phenomenon, and the rise time are very short. The difference between two sensors is the amplitude value, and the attenuation coefficient is calculated as follow.

$$AC1=\frac{V_{before}}{V_{after}} \tag{3}$$

Where, V_{before} is the signal amplitude before through the PE layer, V_{after} is the signal amplitude after through the PE layer.

By analyzing repeated experiment results, the attenuation coefficients are shown in fig.8. It can be seen from the results that the attenuation coefficients distribute at the range from 3 to 5.

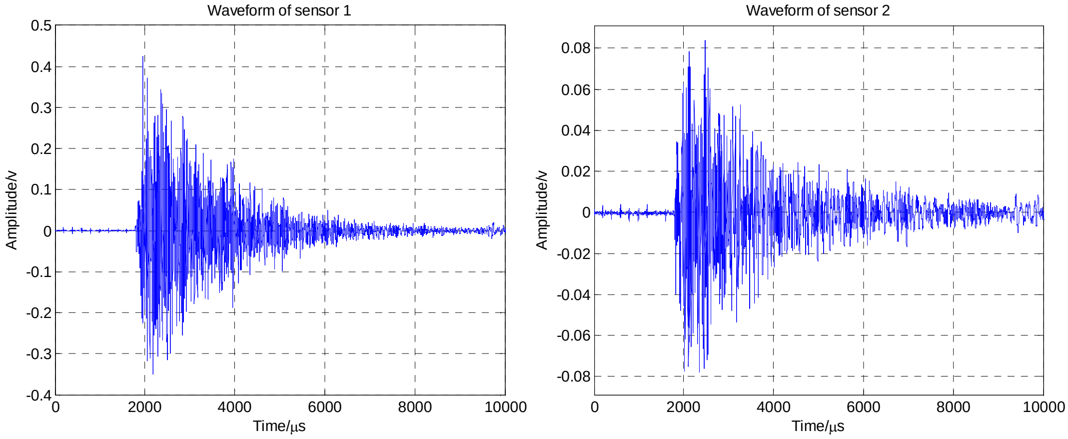
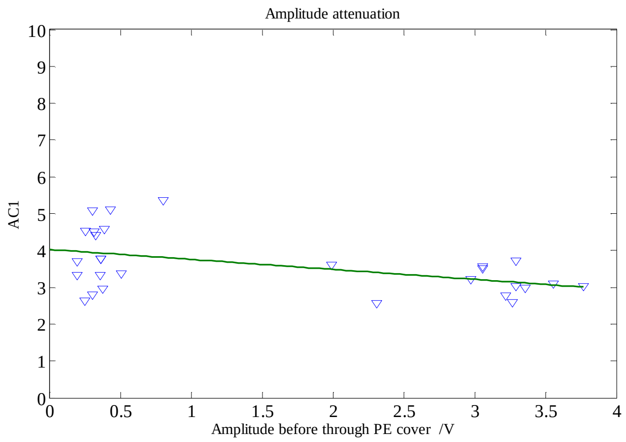


Fig.7 Waveform collected by sensor1 and sensor2



Fif.8 Amplitude attenuation when the wave through PE layer

The frequency spectrum of the signals from sensor 1 and sensor 2 are shown in fig.9. It can be seen from the spectrum that the signal from sensor 1 is divided into three frequency band, the first band is from 0.008 to 0.025MHz, the second band is from 0.038 to 0.095MHz, and the third band is from 0.136 to 0.155MHz. The main energy distributes in the second band, and focus on the range from 0.038 to 0.055MHz. the signal from sensor 2 also contain three frequency band, the first band is from 0.005 to 0.03MHz, the second band is from 0.042 to 0.056 MHz, and the third band is from 0.148 to 0.155MHz. The main energy also distributes in second band, and concentrates on 0.045MHz.

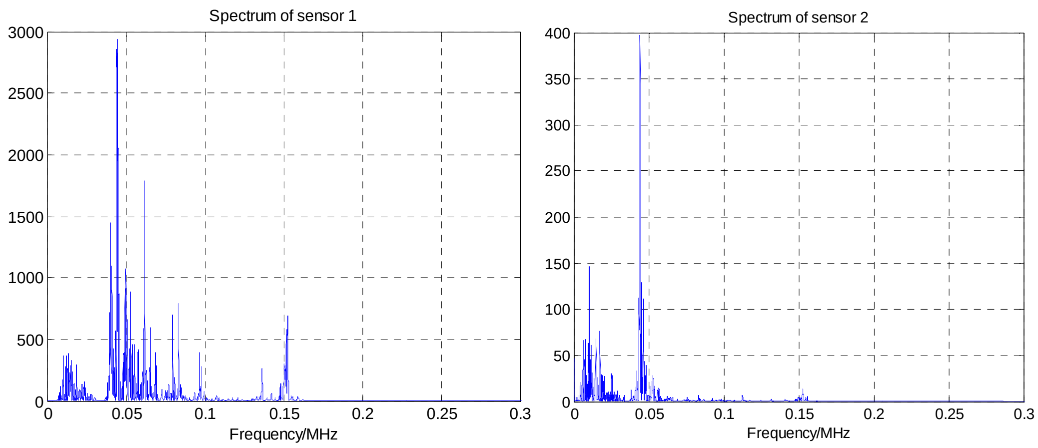


Fig.9 Spectrum of the signals from sensor1 and sensor2

The spectrum illustrates that there are many similar characteristics by comparing the signal from sensor1 and sensor2, such as, all spectrums have three frequency bands and the range of bands are similar, the main energy distributes in the second band and most of energy are focus on 0.048MHz, and the energy distribute in the third band is low. There are also some differences between two sensors, such as, the spectrum of sensor2 has less frequency components and the peak frequency is more prominent. In generally, when the stress wave though PE layer, its spectrum like been filtered, but the main characteristic retained.

Comparing the waveform collected by sensor1 and sensor2 synthetically, when the stress wave through PE layer, the main changing is the attenuation of amplitude and energy, but the frequency spectrum characteristics are remained.

Waveform Difference in Different Section Position

Stress wave will propagate in cables for a long distance until the energy attenuation to zero. Even the source generated in center wires, it will be collected in center wires and edge wires. By comparing the signal collected by sensor7 and sensor8 shown in fig.10, it can be seen that the amplitude in center sensor is slightly higher than that in edge sensor. Repeated tests are carried out in same conditions and the attenuation coefficient is calculated by Eq. (4), and the results are shown in fig.11.

$$AC2=\frac{Vcenter}{V_{edge}} \qquad (4)$$

Where, V_{center} is the signal amplitude in center wires, V_{edge} is the signal amplitude in edge wires.

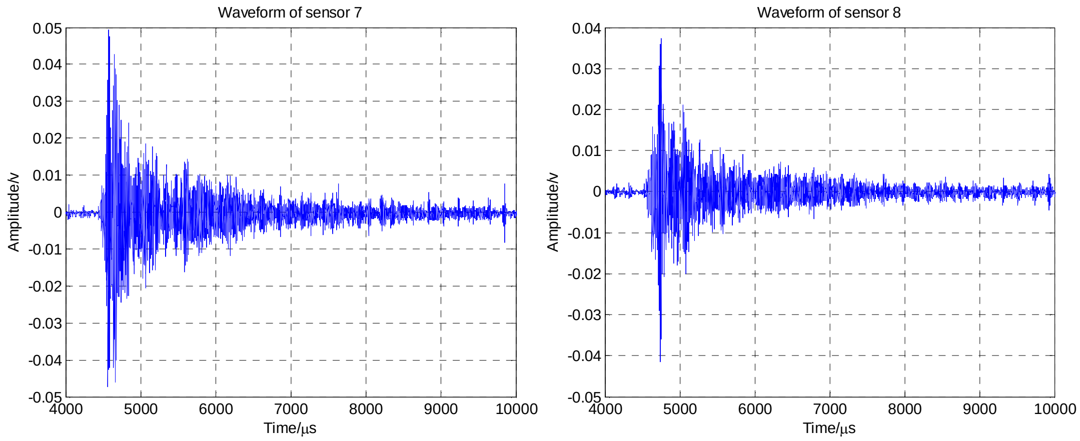


Fig.10 Waveform collected by sensor7 and sensor8

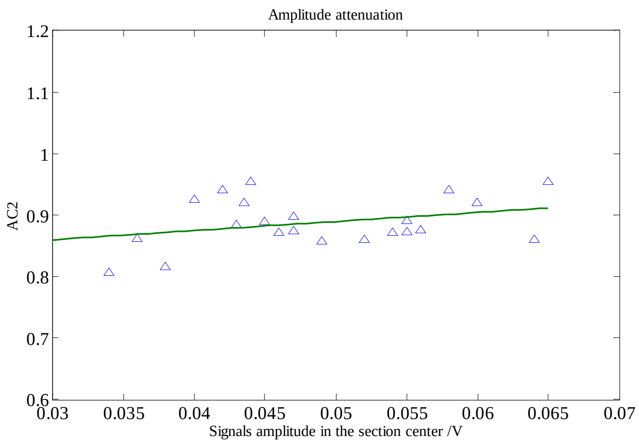


Fig.11 amplitude attenuation between center wires and edge wires

The spectrum of the signal collected by the two sensors are shown in fig.12. The two spectrum all have five frequency bands, and the range of bands is shown in tab.1.

Among the five bands, the second and third bands hold the most energy and the third band is more obvious. The energy distributing in other three bands is very little, especially in the first band.

The signal from sensor8 is similar to sensor 7, but the peak frequency is less prominent than sensor 7.

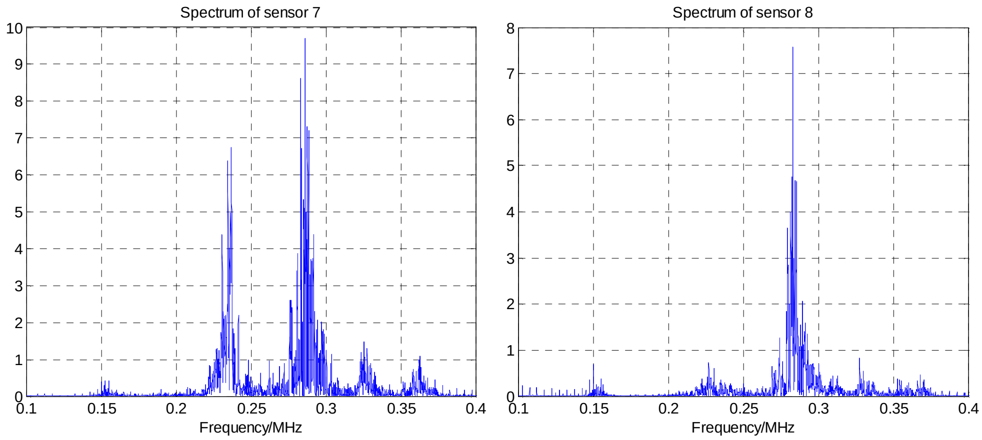


Fig.12 Spectrum of the signals from sensor7 and sensor8

Tab.1 Frequency band distribution

Bands number	Bands position（MHz）
1	0.147-0.16
2	0.22-0.25
3	0.27-0.30
4	0.32-0.34
5	0.36-0.37

Comparing the spectrum of sensor7 and sensor8, it can be seen that both the frequency band position and bandwidth are similar, and the difference is energy value and the proportion among in difference band.

In general, the waveform and spectrum between signals from sensor7 and sensor8 have a great many of similarity, which illustrate that the waveform will became similar when it take a long propagation distance, and will evenly distribute in whole cross section.

Energy Attenuation in Cable Length Direction

As the analysis above, the main changing of stress wave propagation in cables are the amplitude and energy, even through the PE layer, the main spectrum characteristics still retained. The following work is to analyze the energy attenuation laws by the signals collected in cable surface. The sources of damage have two types, the first one is the impact in end section of tension free cable; the second one is wire breakage in tensioning cable. The magnitude of the attenuation is usually described by attenuation ratio. The attenuation ratio is decided by the material properties, cross-section shape, wave frequency and so on, but when the material properties and section shape are given, it is a function of wave frequency.

The energy attenuation law in cables not has theoretical solution so far, and it assumed to satisfy exponent model as follows.

$$E = E_0 \exp(-\alpha x) \tag{5}$$

Where, E is the accumulative energy of stress wave; x is propagation distance; E_0 is the initial energy at the wave source; α is the attenuation factor. The energy is defined as follows,

$$E = \sum_{i=1}^{n} a_i^2 \tag{6}$$

Where, n is sample number of full-waveform, a_i is value of the ith point. If the experimental damage is similar to the real cable, the effects of frequency can be ignored. Then, the attenuation factor is calculated as follow.

$$\alpha = -\frac{\ln E_2 - \ln E_1}{(x_2 - x_1)} \tag{7}$$

According to the exponent model and logarithm transformation, the attenuation curve is drawn in fig.13. The red line is fitted by the measured data from tensioning cable, and the blue line is fitted by the measured data from tension free cable. By repeatedly testing, the mean value of attenuation factor is shown in tab.2.

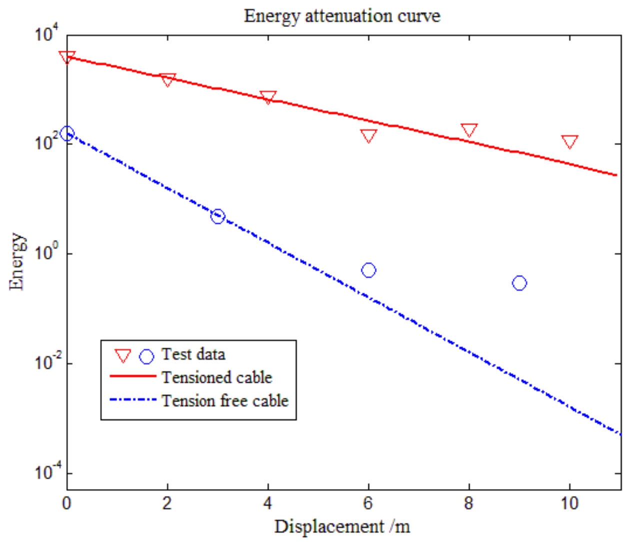


Fig.13 Logarithmic curve of energy attenuation

Tab.2 Mean values of energy attenuation factor

Conditions	Attenuation factor	Peak frequency（KHz）
Tension free cable	1.149	44
Tensioning cable	0.447	43

It can be seen from tab. 2 that the factors in two conditions are different obviously. The value in tension free cable is higher than that in tensioned cable, which maybe affect by the stress among wires. However, in the experiments of tensioning cable, because the tension force increases step by step, the difference wire breakage signals have difference tension force, but the attenuation factors are close to 0.447. This phenomenon means that the tension force will affect energy attenuation rate, but after the cable is straining, greater tension force will not minish the attenuation factor, and generally the straining force is twenty percent of cable yield force.

Discussion

The work in this paper is through experiments to find out the changing laws when the stress wave propagating from PE inside to outside, the distribution laws in cross section when it have a long propagation distance, and energy attenuation model measured in PE outside. Through analyzing the experiment data, the result illustrate that when the stress wave have a long propagation distance, it will have similar waveform and spectrum characteristics in section center and edge. When the stress wave propagates from PE inside to outside, main changing in this process is the attenuation of amplitude and energy, but the spectrum characteristics are remained.

So, for the process of stress wave propagate from center wires to edge wires, and finally reach to the PE outside, its spectrum characteristics such as bandwidth and peak frequency will invariable. The change only occurs in amplitude and energy, and it has been fitted by an exponent formula based on experimental data. In the two difference conditions, the fitted attenuation factors are difference, the mean value in tension free cable is higher than that in tensioned cable. The main reason for this phenomenon is the compact force among difference wires, and the tensioned cable have greater force than tension free cable, which will make the energy loss little.

Conclusions

Through carry out experiments in tension free cable and tensioned cable, there are some conclusions about the stress wave propagation in cables have been found.

The stress wave propagates in cables will change obviously. If the damage monitoring methods do not consider the influence of wave propagation distance, the assessment result based on AE is imprecise. By using the data collected in PE surface to fit the energy attenuation laws, the result illustrate that energy attenuation conform to exponent model, and the attenuation factor in tension free cable is higher than that in tensioned cable. When the stress wave through PE layer, it will attenuate in amplitude and energy, generally attenuate to the range from 1/5 to 1/3, but the main spectrum characteristics such as peak frequency and frequency distribution will retain. Stress wave propagation in cables with a long distance will distribute in whole cross section homogeneously. The spectrum cumulated by collected data in PE outside can present that wave propagate in cable inner.

Acknowledgements

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