Structural Health Monitoring for Cables with Insulation Layer by Envelope Analysis Based on Ultrasonic Guided Waves

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Abstract. Cables play an important role in industries and their insulation layer may experience aging problems, which can lead to serious consequences such as fire. Therefore, monitoring the condition of the cable insulation layer can effectively avoid accidents. In this paper, a structural health monitoring method for cables with insulation layer is proposed, which is based on ultrasonic guided waves (UGWs). In the method the UGWs are generated by MFC transducers and do not affect the normal operation of the cables. When UGWs propagating in the cable encounter defects, the reflected signals appear and can be acquired by the measurement system. The signal received by MFC transducers is processed to extract the characteristics. According to the envelope of received signals, it can be judged whether the current cable insulation is defective. In the experiment, cables in different conditions are tested and defects are successfully detected.

1. Introduction

As a medium for transmitting electric energy and signals, cables have been widely used in many fields. Most of the cables are wrapped by protective insulation layer. The safety of the cable is a big issue that cannot be ignored, once the cable has a hard fault (short circuit or open circuit), it may cause a fire leading to catastrophic consequences and loss of life and property. Most of the cable accidents are due to problems with the insulation, therefore, it is very important to monitor the health condition of the cable insulation layer [1].

Researchers have used a variety of methods to detect cable defects. Traditional methods [2] include visual inspection, insulation resistance inspection and breakdown method, etc. Modern detection methods include time domain reflectometry (TDR), pulse spark discharge method (PASD), and ultrasonic guided waves (UGWs) method, etc. Lee et al. [3] combined machine learning and TDR to detect and identify defects in multi-core cables. Schneider et al. [4] used PASD to conduct experiments on a cable with a length of 30 m. The experimental results show that PASD is capable of detecting insulation defects such as cracks and chafes. Both TDR and PASD need to transmit a pulse signal to the tested cable and then reflected signal is analyzed to locate a defect, hence they cannot realize online monitoring.

As a technique for non-destructive testing and structural safety monitoring, UGWs are widely used in various occasions due to their advantages of long propagation distance and low attenuation [5].
Yucel et al. [6] used UGWs method to detect overhead cables and studied the influence of defect size on guided wave propagation. Zhang et al. [7] analyzed the propagation of guided waves in multi-wire cables from the aspects of frequency dispersion and wave structure and studied the energy distribution of different layers in the aluminum core steel reinforced cable. The UGWs method can detect the defects of the cable insulation layer in the early stage of the fault, and this method does not affect the cables’ working status [8]. The above-mentioned research mainly focuses on bare stranded wires, and this paper analyzes the defect detection of the cables with insulation layer.

In this paper, UGWs method is used to detect a single-core cable. An experiment system is designed to realize online monitoring of the cable, which mainly contains computer, DAQ, MFC transducers, power amplifier and signal amplifier circuit. The status of the cable can be judged in real time.

2. Theoretical Analysis

The wave equation in a uniform and isotropic solid can be expressed by Navier governing equation [9]:

$$\mu \nabla^2 \mathbf{u} + (\lambda + \mu) \nabla (\nabla \cdot \mathbf{u}) = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}$$

(1)

where $\lambda$ and $\mu$ are the Lamé constant, $\mathbf{u}$ is the displacement vector, $\rho$ is the medium density, and $t$ is the time.

In a multilayer structure such as a cable, UGWs not only propagate in the insulation, but also propagate in the inner conductor. The continuous conditions of velocity and stress are satisfied at the boundary of different media. The dispersion equation in the cable can be obtained by combining boundary conditions with equation (1).

When the UGWs propagate in the cable and encounter a defect, a reflected signal appears, which is caused by the change of the acoustic impedance at the defect. The contact between the UGWs and the defect in the cable can be regarded as vertical incidence, and the reflection coefficient satisfies the following equation (2):

$$R_{12} = \frac{Z_{a2} - Z_{al}}{Z_{a1} + Z_{a2}}$$

(2)

where $R_{12}$ is the ratio of the reflected sound pressure to the incident sound pressure, $Z_{al}$ and $Z_{a2}$ are the acoustic impedance of the two media respectively.

The ratio of the intensity of the reflected wave to that of the incident wave is as equation (3):

$$\frac{I_R}{I_I} = \left(\frac{Z_{a2} - Z_{al}}{Z_{a1} + Z_{a2}}\right)^2$$

(3)

At the location of the cable defect, the media at both ends of the boundary are insulating material and air or metal conductor and air respectively. The acoustic impedance of air is much smaller than that of insulation or conductor, in this situation, the reflection coefficient is approximately equal to 1, which can be regarded as total reflection. The reflected wave and the incident wave are equal in magnitude and opposite in phase. By analyzing the characteristics of the reflected signal, the current status of the cable can be judged.

3. Experiment system

In the experimental system shown in figure 1, a NI USB-6366 data acquisition card is used, which generates driving signal of the transducer with the computer through the LabVIEW program. The signal from DAQ is amplified by the power amplifier to excite the MFC transducers to generate UGWs. The reflected signals received are amplified and processed in the computer.
The excitation signal used in the experiment is a 20 KHz sinusoidal signal of 5 cycles modulated by a Hanning window. The signal has good SNR and echo resolution. The excitation signal is shown in figure 2.

In the LabVIEW program, the collected data is filtered in real time and the envelope is extracted, so that the signal can be seen more intuitively. A zero-phase filter is adopted, which does not produce phase shift to affect the detection result. The envelope of the filtered signal is obtained after Hilbert transform. Between the first received signal and the end reflected signal, if a new envelope appears and its peak value is higher than the threshold set in advance, it indicates that the cable is defective. These peaks and their corresponding appearance times can be displayed in the front panel of the program.

4. Experiments and Results
In the experiment, a H07V-K single-core control cable manufactured by Lapp is selected, which complies with EN 50525-2-31 and IEC 60332-1-2 standards. The MFC transducers are set to ‘one-transmit-one-receive’ mode. The MFC transducers are excited to generate an L(0,1) mode guided wave, thus reducing the influence of dispersion [10]. Three kinds of cable defect detection experiments are carried out in this paper.

4.1. Single defect with insulation layer completely peeled off
A 2 m-long cable is selected, and the transmitting and receiving MFC transducers are fixed at the head end and 1m away from the head end respectively. A 10 mm-long defect with insulation completely
peeled off is set at a distance of 1.5 m from the head end. The received signal of the non-defective and defective cables is shown in figure 3(a) and (b). The blue curve represents the envelope of the normalized received signal.

![Figure 3. Received signal when there is a 10 mm-long defect at a distance of 1.5 m from the head end. (a) Non-defective cable. (b) Defective cable.](image)

Comparing figure 3(a) and figure 3(b), it can be found that the number of peaks in figure 3(b) is one more than that in figure 3(a). Two peaks which appear at 505 μs and 1160 μs in figure 3(a) and (b) represent the first signal received by the transducer and the reflected signal at the end of the cable. The second peak appearing at 810 μs in figure 3(b) represents the defect reflected signal.

4.2. Single defect with insulation layer chafed
In this case a 2 m-long cable is selected and a 25 mm-long chafe defect is set at 1.5 m away from the head end. The detection results are shown in figure 4(a) and (b). Figure 4(b) also shows the defect reflected signal appearing at 810 μs.
4.3. Double defects with insulation layer chafed

Two 15 mm-long defects with completely peeled-off insulation are set on a 3 m-long cable, and the defects are respectively 1.75 m and 2.5 m away from the head end. Figure 5 shows the detection result, two defect reflected signals which appear at 1060 μs and 1510 μs are successfully detected.

Figure 5. Received signal when there are two 15 mm-long defects which are 1.75 m and 2.5 m away from the head end respectively. (a) Non-defective cable. (b) Defective cable.
5. Conclusions
This paper presents a structural health monitoring method for cables with insulation layer based on UGWs, which can detect the defects of the cable insulation without destroying the structural integrity of the cable. The generation and acquisition of the signal are controlled by the LabVIEW program, meanwhile, the signal received by the MFC transducers is filtered and the envelope is extracted. According to the peak number of the envelope, the current structural safety of the cable can be judged. In this paper, three different kinds of cable defect detection experiments are carried out, and the results show that this method can detect the cable insulation defects.

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