나노-TDR센서를 이용한 토목구조물 모니터링 시스템

Application of Nano-TDR Health Monitoring System in Civil Engineering

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Abstract

This study presents reasonable relationships to estimate the deformation based on beam mechanism analysis and TDR(Time Domain Reflectometry) data. To declare the length points of co-axial cable installed in civil structure, Nano material ($BaTiO_3$ powders and silver mixture) is used on co-axial cables. From the laboratory test, nano material could make the correct information about attached cable points on beam, and TDR sensor system and Fourier series (data filter) found out the deformation of beam. Therefore it is concluded that the correct deformed information of beam were acquired by Nano-TDR and Fourier filter, they are much more effective to apply at health monitoring system in civil structure compared to conventional TDR or Fiber Optic Sensor (FOS) systems.

요　지

이 논문은 나노물질이 결합된 시간반사영역기(TDR)의 보의 변형에 관한 실험자료와 기존 구조 해석기법에 따른 변형간의 상관관계를 평가하기 위한 것이다. TDR의 동축케이블에 일정한 간격마다 나노물질($BaTiO_3$ powders and silver mixture)을 결합하여 토목구조물에 설치할 수 있도록 하였다. 실험결과,나노물질은 보에 설치된 동축케이블의 정확한 위치정보를 알려주었으며, TDR센서시스템과 Fourier series를 활용하여 필터링 된 실험 자료는 보의 변형을 정확하게 알려주었다. 그러므로, 나노-TDR시스템과 Fourier filter를 활용하여 보의 변형에 관한 정확한 모니터링이 가능하였으며, 변형에 관한 보다 나은 해석이 가능하다는 점에서 기존의 TDR센서 혹은 광섬유 센서보다 진보한 시스템이라 할 수 있다.

Keywords : Beam deformation, Differential analysis, Fourier series, Nano-material, TDR

핵심 용어 : 보 변형, 미분방정식, 푸리에 시리즈, 나노물질, TDR

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1. Basic Theory on Nano-Tdr

Most civil structure performance assessment, e.g., damage, failure, and non-destructive inspection approaches, are difficult to execute on hard-to-reach elements of a structure. These routine methods are also time-consuming, with uncertainties involved and not cost-effective because of technologies limits. In civil engineering field, the monitoring of element of a long-type structure by Time Domain Reflectometry 栀槃搀犲 or Fiber Optic Sensor 栀FO獓 is aimed at early detecting of the safety of structure through the analysis of obtained deformation data at numerous points along the axis of the element.

Fiber optic cable is so brittle, because it is composed of the glass (SiO_2) which would be broken by small impact. Therefore fiber optic cable could not be used in field. However, TDR sensor system is so strong, it overcomes the tough field conditions because co-axial cable is used as sensor itself directly. Additionally, to get correct information on cable points, nano materials are suggested and tested to adopt the tough field conditions.

1.1 TDR Theory

TDR is a relatively new approach to monitoring civil structure. Originally developed to locate breaks and faults in communication and power lines. Also, TDR is the method of sending a fast pulse down a transmission line, and then monitoring the reflection signal returning back from impedance changes along the line. Fig. 1 shows a schematic diagram of a typical TDR configuration.

The transmission line typically consists of a

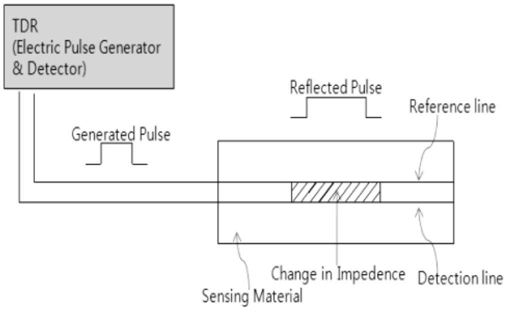

Fig. 1 Configuration of Typical TDR system

co-axial cable and two parallel conductors. The two conductors are embedded within the material or surface-mounted on the material as sensors to monitor local changes in material properties. If the pulse encounters a deformation or the end of the cable, part or all of it is reflected. The returned pulse is compared with the emitted pulse, and the reflection coefficient (in rho's or millirho's) is determined[(1)-(3)].

The amplitudes of the reflections in a TDR signature indicate the severity of damage to the cable. Changes in amplitude with time correspond qualitatively to the rate of structure deformation [(1)(2)].

The speed at which the pulse travels down the cable as a percentage of the speed of light is called the velocity of propagation and is a property of each cable. By knowing the velocity of propagation, the distance to, and the type and severity of any cable fault can be determined 1.

Coaxial cables are composed of a central metallic conductor surrounded by an insulating material, a metallic outer conductor surrounding the insulation, and a protective jacket (Fig. 2).

If the inner and outer conductors changes as does the impedance at that point. Changes in material spatial properties can be related to changes in local impedances in the vicinity of

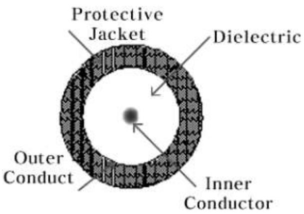

Fig. 2 Section of Coaxial Cable

the sensor, which result in attenuation/increase in the reflection signal as well as propagation delay. Therefore, investigating reflection signals provides useful information on the local material properties, since material properties or structural status (such as moisture contents, phase trans-formation, density, crack size, chemical adsorption or desorption and locations)and structural failure locations can be correlated with dielectric, magnetic, and electric properties, as well as geometry changes (or discontinuities) in the vicinity of the sensor.

1.2 Nano Material Deposition

Direct writing processes were defined to any technique or process capable of depositing, dispensing, or processing (including subtractive) different types of materials over various sur-faces following a preset pattern or layout. Manufacturing processes characterized by the use of computer-generated patterns and shapes for direct fabrication without part-specific tooling.

Ink jet printing, nscrypt and M^3D (Maskless, Mesoscale, Materials Depostion) were equipped in SDSMT (South Dakota School of Mines and Technology) campus. Photo 1 shows the M^3D machine which was used for the deposition of nano sized $BaTiO_3$ powders and silver mixture for the Nano-TDR.

Photo 2 shows the deposited nano materials between the two transmission copper line. In this study, $BaTiO_3$ (dielectric constant : > 6,000) and conductive silver nano particles were de-posited for Nano-TDR using M^3D at SDSMT Campus. There are multitude of different ways to create metallic and metal oxide particles, in this study silver nanoparicles were created using inverse-micelle method and then commercial $BaTiO_3$ nano powders were mixed with nano silver powders in aqueous system. This reliable method for creating dispersing nanoparticles in

Photo 1 M^3D system with control electronics outlined in red-dashing, door to environmentally controlled enclosure outlined in yellow-dashing, and computer interface outlined in white-dashing.

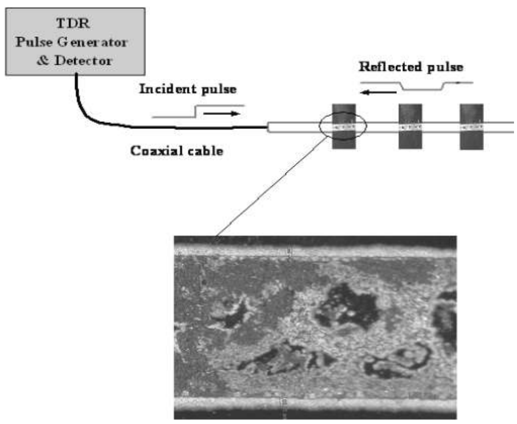

Photo 2 Configuration of Nano-TDR with nano $BaTiO_3$ and silver mixture

aqueous system for M^3D could produce less than 100 nm particle distribution without particle aggregation and agglomeration. Finally, nano particles dispersed in aqueous were used to create Nano-TDR patterns with the 25 micron line resolution in M^3D. This high dielectric material adjusted with conductive silver particle was designed to sensitively respond to incident pulse signal from TDR generator[(4)-(7)].

2. Data Analysis

To analyze beam extension, the co-axial cable is installed on the surface of beam and connected to the TDR system. To eliminate noise in raw data, Fourier series is used as an approximation of the calculated displacement. The measured data by TDR have difficulties to check the deformation of beam directly. Therefore, differential equation and noise filtering by Fourier series were used to analyze the data of beam extension.

2.1 Differential Equation of Beam Deformation

After laterally loading, the beam gets a pure-bending, or the axis of the beam becomes a curve with a curvature radius, *R*, as shown in Fig. 3 Two end sections of the beam separated by distance *l*, under local reference frame, will intersect after bending at an angle θ which equals to *dl/R*, where *l*, is the original length of the beam[(8)].

Let *h* is the thickness of the beam, ε_u and ε_l are strains of upper and lower surface portion measured by TDR, respectively. Generally speaking, elongating strain ε_u is signed "+" and inversely, compressing strain ε_l is "−", and $|\varepsilon_u| = |\varepsilon_l|$, or, $\varepsilon_u = -\varepsilon_l$.

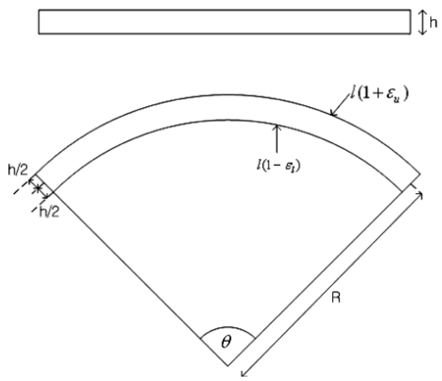

Fig. 3 Geometrical model of pure bending of beam

Obviously,

$$\theta = \frac{l(1+\varepsilon_u)}{R+h/2} = \frac{l(1+\varepsilon_l)}{R-h/2} \tag{1}$$

and from above,

$$R = \frac{2+\varepsilon_u+\varepsilon_l}{\varepsilon_u-\varepsilon_l}\cdot\frac{h}{2} \tag{2}$$

For pure bending, symmetrical, constant section of straight beam, we have, $\varepsilon_u = -\varepsilon_l = \varepsilon$ so that

$$R = \frac{h}{2\varepsilon} \tag{3}$$

This means the local radius of curvature is a function of relevant measured strain.

Considering the length of the neutral axis keeps constant, then the deflection(noted as y) of the beam from its initial position is as follows,

$$y'' = -\frac{1}{R} = -\frac{2\varepsilon}{h} \tag{4}$$

$$y = -\left(\frac{\varepsilon}{h}\right)\cdot x^2 + c_1 x + c_2 \tag{5}$$

And c_1 and c_2 are calculated on conside ring initial conditions of each fixed ends.

2.2 Data Filtering

If the measured data contains noise which is irregular signals with time, the data noise should be eliminated to get correct tendency of beam deformation. To do that, in this research two methods were used; those are 1) moving average for low band filtration, 2) Fourier series for shape estimation.

Moving average was used at first to delete the noise of low frequency happened in raw data (equation (6), first filter), then filtered data by moving average method is sent to the second filter made by Fourier series again (equation (7~10), second filter).

$$q_n = \frac{f_{n-1} + f_n + f_{n+1}}{3} \tag{6}$$

Fourier series has two types of functions, Fourier cosine series and Fourier sine series. They are selected by the shape of raw data functions[9].

The Fourier series of an even function f(t) of period T is a "Fourier cosine series"

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos\frac{2n\pi}{T}t \tag{7}$$

[even f(t))

with coefficients

$$a_0 = \frac{2}{T}\int_0^{T/2} f(t)dt$$
$$a_n = \frac{4}{T}\int_0^{T/2} f(t)\cos\frac{2n\pi}{T}tdt \tag{8}$$

n= 1, 2, ⋯..

The Fourier series of an odd function f(t) of period T is a "Fourier sine series"

$$f(t) = \sum_{n=1}^{\infty} b_n \sin\frac{2n\pi}{T} \tag{9}$$

(odd f(t))

with coefficients

$$b_n = \frac{4}{T}\int_0^{T/2} f(t)\sin\frac{2n\pi}{T}tdt \tag{10}$$

To estimate the deformation of beam, differential equation and Fourier series were used at the same time. However their processes are totally different and compared after each calculation finished. Calculation process of them is shown in Fig. 4.

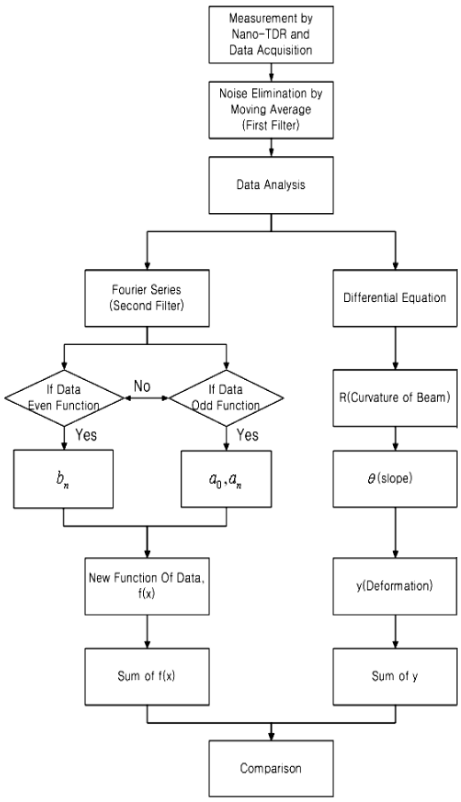

Fig. 4 Analyzing Process of Deformed Beam

3. Experimental Verification

For this experiment, nano material was used for examining of correct point of mounted co-axial cable on beam, furthermore to examine the tendency of beam deformation, TDR system was used, respectively. In conclusion, the correct deformed information of beam was acquired by them.

3.1 Nano Material

Nano particles dispersed in aqueous were used to create Nano-TDR patterns with the 25 micron line resolution in M^3D. This high dielectric material adjusted with conductive silver particle was designed to sensitively respond to incident pulse signal from TDR generator. As seen in Fig. 5, nano material mixtures of $BaTiO_3$ and silver show exact position of these materials in Nano-TDR, with this method, nano material can be used for position sensor.

3.2 Deformed Beam Analysis

Fig. 6 shows a lab experimental flexible PVC pipe whose outer radius is 5cm, thickness 0.3 cm, length 70cm. Coaxial cable was installed on the surface of the pipe with epoxy and silicon material. The deformation along whole pipe seems to be symmetrical but not real case due to non-confirmable influential factors such as heterogeneity of PVC material, deflective loading etc.

It should be noted that each measured point has the information about fixed segmental length (10cm) as initial conditions for differential equations analysis. Applied loading was 5kg steel which was hooked at the center of pipe.

The noise-contained displacement can be deduced by a setup of spreadsheet using the differential equations and Fourier series. Initially, subtracting corresponding reference strain me-asurements from the strain measurements after loading is first step for differential equations and Fourier series analysis both.

Fourier series is mainly for data filtering, it processes only data noise. Therefore, after data processing, filtered data should be sent to differential analysis. If all processes including first filtering(moving average), second filtering (Fourier series) and differential analysis are finished, the smooth graph to show real de-formation of beam will come out. Please note that the value from TDR is time difference not

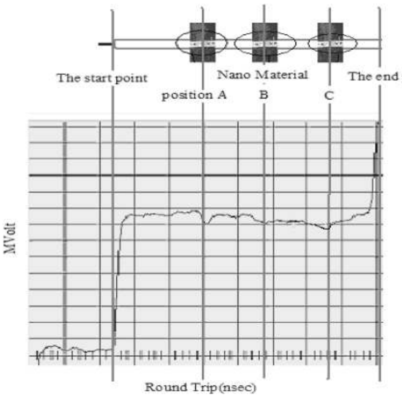

Fig. 5 Positioning of Cable by Nano Material

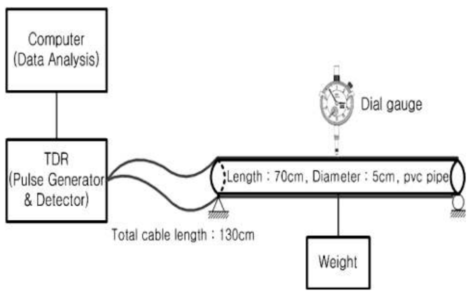

Fig. 6 Lab Experiment

deformed length, it means we need another step, differential analysis. The measured data means data difference between before bending and after bending, they are raw data to be filtered. It is concluded that in this case odd Fourier analysis matches well to the original data function. In this case, raw data is generated as digital number to analyze; it means the equation of Fourier series should be revised to adopt discrete data not continuous function. The Fourier series of an odd function f(t) of discrete data is a “discrete Fourier sine series”. For this experiment calculation iterations are fixed as 9(N=9), it means new filtered data are sum of calculated values of Fourier sine series from 1 to 9(n= 1~9) for raw data control (refer equation 11~12).

$$f(x) = \sum_{n=1}^{9}[b_n \sin(\frac{n\pi x}{L})] \quad (11)$$

[odd f(t))

with coefficients

$$b_n = \frac{2}{N}\sum_{x=0}^{L}[\sin(\frac{n\pi x}{L})f(x)] \quad (12)$$

Table 1 shows the coefficients of Fourier sine and cosine series for the experiment, from the two series, sine series was selected. Therefore a_o and a_n for cosine series were compared but not used, only b_n was adopted for the analysis. In addition, table 2 shows the values of TDR and calculated by Fourier filter. Please note the values of differential analysis means raw data filtered by moving average method (first filter) and processed by differential equation of beam theory.

From those values and equations, the cur-vature calculation of each segment of beam is

Table 1 Coefficients of Fourier sine and cosine series

a_0	n	a_n	b_n
0.0370	1	0.005	0.664
	2	−0.068	0.079
	3	−0.012	−0.564
	4	0.053	−0.119
	5	0.01	0.394
	6	−0.03	0.098
	7	−0.01	−0.199
	8	0.01	−0.018
	9	0.00	0.031

Table 2 Values of TDR and calculated by Fourier filter

Cable length	Initial value of TDR	TDR value after loading	Diff. analy−sis only	Even Four−ier	Odd Four−ier
0.00	40.81	40.52	0.00	0.40	0.00
0.10	41.50	40.81	0.00	0.41	0.00
0.20	42.09	41.69	0.00	0.44	0.01
0.30	42.29	42.09	0.00	0.45	0.02
0.40	42.19	42.09	0.00	0.48	−0.01
0.50	42.09	42.29	0.00	0.61	−0.06
0.60	41.99	42.19	0.00	0.90	0.00
0.70	42.49	42.29	0.00	1.21	0.39
0.80	42.79	42.19	1.29	1.21	1.08
0.90	42.69	42.29	0.86	0.65	1.72
1.00	42.59	42.09	1.07	−0.28	1.85
1.10	43.51	42.79	1.52	−1.04	1.34
1.20	43.82	43.61	0.00	−1.25	0.55
1.30	43.92	43.61	0.00	−0.94	−0.01

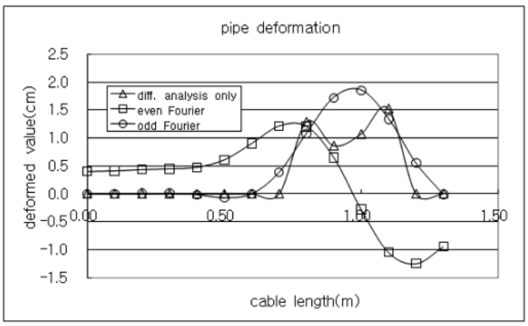

Fig. 6 Fourier Filtered Graph

starting point of differential analysis, and then slope and deformation of each pipe segment are calculated. Before filtering, they give only the rough patterns of pipe deformation. That means conventional differential analysis also needs data filtering. Fig. 6 shows the graph acquired by differential analysis. The difference of differential analysis and filtered plus differential analysis is shown in it. The maximum deformed pipe length by extension is 1.52cm on analysis and 1.85cm on filtering plus, respectively.

Furthermore to evaluate the calculation process, a dial gauge was used to the center of pipe length, which measured the deformed value as 1.78 cm. Because the pipe is small (70cm), it was difficult to set up several dial gauges on it. However it could be told that the deformed value of dial gauge is close to the odd Fourier filtered data.

4. Summary and Conclusion

This study presents relationships to estimate the deformation of beam and Nano-TDR data. To declare the length points of co-axial cable, Nano material ($BaTiO_3$ powders and silver mixture) is used on co-axial cables and TDR sensor system found out the tendency of deformed PVC pipe.

To eliminate noise in raw data, moving average and Fourier series were used as filters. For this research, odd Fourier analysis matches well to the original data function. They were proved as powerful filters for discrete data analysis.

Because unfiltered data give only the rough patterns of pipe deformation, conventional differential analysis also needs data filtering. However if filtered data were used, differential analysis shows good accuracy to the result of the dial gauge measurement (dial gauge result: 1.78 cm, filtered value: 1.85 cm).

In conclusion, the correct information of deformed PVC beam were acquired by Nano-TDR system and filters, they have good accuracy and effective to apply at health monitoring system in civil structure compared to conventional TDR or FOS systems.

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