Design and Research of Structural Health Monitoring System for Stayed Cable Bridge Based on LabWindows/CVI

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Abstract:
The thesis mainly research how to design the health monitoring system for stayed-cable bridge based on LabWindows/CVI, which includes the methods of developing the system and all kinds of theories and technologies applied in the design process. In accordance with the function modules of the system, the design process and used theoretical methods of each module are described, and the application applicability of each function module is verified with demonstrations or experiment.

Keywords:
LabWindows/CVI, Stayed-cable bridge, Structural health monitoring system
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1 Notation

\( f(t) \)  \hspace{0.5cm} \text{Continuous signals in time domain} \\
\( F(\omega) \)  \hspace{0.5cm} \text{Fourier transform} \\
\( F_T(\omega) \)  \hspace{0.5cm} \text{Fourier transform of the signal in period } T \\
\( T \)  \hspace{0.5cm} \text{Period} \\
\( S_f(\omega) \)  \hspace{0.5cm} \text{Power spectrum} \\
\( x[n] \)  \hspace{0.5cm} \text{A digitized time-domain waveform that has a finite length } n \\
\( w[n] \)  \hspace{0.5cm} \text{A window sequence of } n \text{ points} \\
\( I_0(x) \)  \hspace{0.5cm} \text{Zero order modified Bessel function of the first kind} \\
\( \rho \)  \hspace{0.5cm} \text{The unit length mass of cable} \\
\( l \)  \hspace{0.5cm} \text{The length of cable} \\
\( n \)  \hspace{0.5cm} \text{The order of frequency} \\
\( f_n \)  \hspace{0.5cm} \text{The } n\text{-order natural frequency of cable} \\
\( T \)  \hspace{0.5cm} \text{The cable tension force} \\
\( E \)  \hspace{0.5cm} \text{Young’s modulus} \\
\( I \)  \hspace{0.5cm} \text{The area moment of inertia} \\
\( M \)  \hspace{0.5cm} \text{The moment} \\
\( Q \)  \hspace{0.5cm} \text{The shearing force} \\
\( \sigma \)  \hspace{0.5cm} \text{The axial stress of cable} \\
\( A \)  \hspace{0.5cm} \text{The cross sectional area} \\
\( \theta \)  \hspace{0.5cm} \text{The inclination} \\
\( \delta \)  \hspace{0.5cm} \text{The sag-to-span ratio} \\
\( s \)  \hspace{0.5cm} \text{The sag} \\
\( l_0 \)  \hspace{0.5cm} \text{The horizontal length of cable} \\
\( \xi \)  \hspace{0.5cm} \text{Dimensionless parameter in Zui’s practical formulas} \\
\( \Gamma \)  \hspace{0.5cm} \text{Dimensionless parameter in Zui’s practical formulas} \\
\( f_h \)  \hspace{0.5cm} \text{The natural frequency vector of the healthy structures}
\( f_d \)  The natural frequency vector of the damaged structures

\( [\mathbf{K}_j^0] \)  The stiffness matrix of the \( j \)th element positioned within the global matrix

\( [\mathbf{M}^0] \)  The global mass matrix

\( \{\phi_k^0\} \)  The \( k \)th mode shape vector

\( D_j \)  Stiffness reduction factor

\( \{\delta f\} \)  The analytical prediction of the frequency changes

\( \{\Delta f\} \)  Measured frequency changes

\( \nu \)  Poisson ratio
2 Introduction

To secure structural and operational safety and issue early warnings on damage or deterioration prior to costly repair or even catastrophic collapse, the significance of implementing structural health monitoring systems for large-scale bridges has been recognized by bridge engineers. Developing a monitoring system for a large-scale bridge is really able to provide information for evaluating structural integrity, durability and reliability throughout the bridge life cycle and ensuring optimal maintenance planning and safe bridge operation.

In the work, the bridge structural health monitoring system and the software LabWindows/CVI are studied. One bridge structural health monitoring system consists of many components, which are various equipments and system softwares. The aim of the work is to build one software system working for monitoring the stayed cable bridge by using LabWindows/CVI.

On the industry field, LabWindows/CVI has been applied widely as one important software development system. However, it is still very difficult to find the case of building one whole monitoring system software by using LabWindows/CVI. And for those completed systems, their each module is usually developed with different development tools, this results in the high development cost and low work efficiency. So, based on above points, the subject of the thesis has its own practical value and realistic meaning.

To start the work, the structure of the system and what functions the system has should be determined. Choosing advisable theories and technologies to carry out determined functions is the second step. Then the rest assignments, which are the most important parts of the work, are to study how to apply those theories and technologies in the LabWindows/CVI development environment and finish the system.

In this work, the framework of the finished system can be separated into four subsystems, which are Structure Status Monitoring, Load Monitoring, Damage Monitoring & Detection and Data Participation. The main objects of structure status monitoring are the girder, the cable and the tower. In load monitoring what we most interest us are the temperature, wind speed, humidity and ground shake. The cable force monitoring and damage detection for the girder are main modules of the damage monitoring &
detection. The framework of the monitoring system is described clearly in Fig. 2.1.

The finished system is provided with four main functions: Data Acquisition, Data Processing & Calculation, Data Storage and Data Communication. Data acquisition consists of DAQ hardware and DAQ software which have functions: analog to digital converter (ADC), signal amplifier, signal transfer, configuration of DAQ parameters. Data processing & calculation also is one very important module in the system, which includes the filter, window and power spectrum analysis for collected data, and cable force calculation and genetic algorithms used in damage detection. For data communication, write data as the server and read data as the client are carried out by using DataSocket technology. The above figure Fig. 2.2 describes the situation about the system’s functions.

Figure 2.1 Framework chart of the system
In following contents, some background knowledge about stayed cable bridge, bridge SHM system and LabWindows/CVI are introduced firstly. Then main functions of the system are described orderly with introducing used theories and technologies and demonstrations or experiments used to verify the application applicability of each function module.
3 Background Knowledge

3.1 Stayed Cable Bridge

The first known sketch of a stayed cable bridge appears in a book called Machinae Novae published in 1595, but it wasn't until this century that engineers began to use them. In post-World War II Europe, where steel was scarce, Cable stay bridges have begun to be built. Since the first modern stayed cable bridge was built in Sweden in 1955, their popularity has rapidly been increasing all over the world [1].

In Asia [2], especially in China, Korea and Hong Kong, a number of long-span bridges were constructed in recent years and further construction of large numbers of cable-supported bridges are planned.

Figure 3.1 Two constructed stayed cable bridges in China

A stayed cable bridge consists of three principal components, namely girders, towers and inclined cable stays. The girder is supported elastically at points along its length by inclined cable stays so that the girder can span a much longer distance without intermediate piers. The dead load and traffic load on the girders are transmitted to the towers by inclined cables.
High tensile forces exist in cable-stays which induce high compression forces in towers and part of girders.

There are no distinct classifications for stayed cable bridges. However, they can be distinguished by the number of spans, number of towers, girder type, number of cables, etc. There are many variations in the number and type of towers, as well as the number and arrangement of cables. Typical towers used are single, double, portal, or even A-shaped towers, which are shown in Fig. 3.2. Cable arrangements also vary greatly. Some typical varieties, which are shown in Fig. 3.3, are mono, harp, fan, and star arrangements.

Stayed cable bridges may look similar to suspension bridges -- both have roadways that hang from cables and both have towers. But the two bridges support the load of the roadway in very different ways. The difference lies in how the cables are connected to the towers. In suspension bridges, the cables ride freely across the towers, transmitting the load to the anchorages at either end. In stayed cable bridges, the cables are attached to the towers, which alone bear the load [3].

### 3.2 Bridge Structural Health Monitoring System

Structural health monitoring systems have been implemented on bridges in Europe, the United States, Canada, Japan, Korea, China and other countries. Bridge structural health monitoring systems are generally envisaged to [4]:

1. validate design assumptions and parameters with the potential benefit of improving design specifications and guidelines for future similar structures;

2. detect anomalies in loading and response, and possible damage/deterioration at an early stage to ensure structural and
operational safety;
(3) provide real-time information for safety assessment immediately after disasters and extreme events;
(4) provide evidence and instruction for planning and prioritizing bridge inspection, rehabilitation, maintenance and repair;
(5) monitor repairs and reconstruction with the view of evaluating the effectiveness of maintenance, retrofit and repair works; and
(6) obtain massive amounts of in situ data for leading edge research in bridge engineering, such as wind- and earthquake-resistant designs, new structural types and smart material applications.

Structural health monitoring has been a subject of major international research in recent years. The research in this subject covers sensing, communication, signal processing, data management, system identification, and information technology, etc. It requires collaboration between civil, mechanical, electrical and computer engineering among others. The current challenges for bridge structural health monitoring are being identified as distributed and embedded sensing, data management and storage, data mining and knowledge discovery, diagnostic methods, and presentation of useful and reliable information to bridge owners/managers for decision making on maintenance and management.

Successful implementation and operation of long-term structural health monitoring systems on bridges have been widely reported. So far about 40 long-span bridges (with spans of 100m or longer) worldwide have been instrumented with structural health monitoring systems. Typical examples are the Great Belt Bridge in Denmark, the Confederation Bridge in Canada, the Tsing Ma Bridge in Hong Kong [5], the Commodore Barry Bridge in United States, the Akashi Kaikyo Bridge in Japan, and the Seohae Bridge in Korea. There are 20 large-scale bridges in China (including the Hong Kong Special Administrative Region) instrumented with real-time monitoring systems. And this does not comprise the East Sea Bridge (consisting of two stayed cable bridges with main spans of 420 m and 332 m respectively), the Hangzhou Bay Bridge (consisting of two stayed cable bridges with main spans of 448 m and 318 m respectively) and the 3rd Nanjing Yangtze River Bridge (a stayed cable bridge with a main span of 648 m) of which the long-term structural health monitoring systems are currently under design.
3.3 LabWindows/CVI

LabWindows/CVI [6], one production of National Instruments (NI, one company of USA), is a software development environment for C programmers. LabWindows/CVI provides powerful function libraries and a comprehensive set of software tools for data acquisition, analysis, and presentation that you can use to interactively develop data acquisition and instrument control applications. You can edit, compile, link, and debug ANSI C programs in the LabWindows/CVI development environment. Additionally, you can use compiled C object modules, dynamic link libraries (DLLs), C libraries, and instrument drivers in conjunction with ANSI C source files when you develop programs.

The LabWindows/CVI environment is structured around the Workspace window, which is shown in the above figure. The Workspace window contains the following areas:

- **Project Tree**—Contains the list of files in each project in the workspace. Right-click the different elements of the Project Tree to see the list of options available for files and folders.
- **Library Tree**—Contains a tree view of the functions in
LabWindows/CVI libraries and instruments. You can arrange the library functions in alphabetical order, by function name or function panel title, or in a flat list instead of a hierarchical class structure. Right-click the Library Tree and select Find to search for a specific function within the tree.

- **Window Confinement Region**—Contains open Source, User Interface Editor, Function Tree Editor, and function panel windows.

- **Debugging Region**—Contains the Variables, Watch, and Memory windows. Use these windows to view and edit variable values and program memory during debugging.

- **Output Region**—Contains the Build Errors, Run-Time Errors, Source Code Control Errors, Debug Output, and Find Results windows. These windows contain lists of errors, output, and search matches.

- **Source Code Browser**—Contains browse information for selected files, functions, variables, data types, and macros in a program.
4 Data Acquisition and Processing

In the process of bridge monitoring, it is the primary way of realizing the structure’s status that signals containing the information about bridge are collected by data acquisition system and analyzed. So, data acquisition (DAQ) and data processing certainly are essential parts of bridge monitoring system.

Figure 4.1 Flow chart of data acquisition and data processing

In the past decade significant progress has been made both in data acquisition technology and data processing theories. In the section, the basic knowledge of DAQ and some fundamental data processing theories used in the thesis will be introduced. Fig. 4.1 shows the flow stages of data acquisition and data processing.
4.1 DAQ System

Data acquisition systems, as the name implies, are products and/or processes used to collect information to document or analyze some phenomenon. In the simplest form, a technician logging the temperature of an oven on a piece of paper is performing data acquisition. As technology has progressed, this type of process has been simplified and made more accurate, versatile, and reliable through electronic equipment. Equipment ranges from simple recorders to sophisticated computer systems. Data acquisition products serve as a focal point in a system, tying together a wide variety of products, such as sensors that indicate temperature, flow, level, or pressure [7].

![Figure 4.2 Basic Framework of DAQ System [8]](image)

Data acquisition involves gathering signals from measurement sources and digitizing the signal for storage, analysis, and presentation on a PC. Data acquisition (DAQ) systems come in many different PC technology forms for great flexibility when choosing your system. Scientists and engineers can choose from PCI, PXI, PCI Express, PXI Express, PCMCIA, USB, IEEE 1394, parallel, or serial ports for data acquisition in test, measurement, and automation applications. There are five components to be considered when building a basic DAQ system (Figure 4.2) [9]:

- Transducers and sensors
- Signal conditioning
- DAQ hardware
- Driver and application software
4.2 Theories of Data Processing

Various information ensconced in the collected data can be shown with data processing. Basic theories used in the thesis are of digital signal processing, which includes power spectrum, window and digital filter.

4.2.1 Theory of Power Spectrum [10]

One way to look at a signal is in the discrete time domain, which puts a series of values consecutively in time. In this way we can tell something about the behavior of the signal at every moment in time, and can also make some simple statements about its long-term behavior. However, it is rather difficult to say anything about how the long-term behavior is related to the short-term development of the signal. Another way to look at a signal is to view its spectral density (i.e., the Fourier transform of the signal). The Fourier transform views the signal as a whole. It swaps the dimension of time with the dimension of frequency. If our signal $f(t)$ represents values in every single moment of time, its Fourier transform $F(\omega)$ represents the strength of every oscillation in a holistic way in that interval of time. These two signals are related to each other by the following formula.

$$ F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt \quad (4.1) $$

The Fourier transform analysis assumes the life of a signal from $-\infty$ to $\infty$. For that reason when an analysis is carried out for a finite amount of time, it is either assumed that the signal is periodic or that it has a finite amount of energy. A true power spectrum of a signal has to consider the signal from $-\infty$ to $\infty$. However, we are not always able to observe a signal that way or derive precise functions for it. We can define $F_{T}(\omega)$ which is the Fourier transform of the signal in period $T$, and define the power spectrum as the following:

$$ S_f(\omega) = \lim_{T \to \infty} \frac{1}{T} |F_T(\omega)|^2 \quad (4.2) $$

The power spectrum itself is the Fourier transform of the auto-correlation function. Auto-correlation function represents the relationship of long and short-term correlation within the signal itself.
4.2.2 Theory of Windowing

Almost every application requires us to use finite length signals. This requires that continuous signals be truncated using a process called windowing.

The simplest window is a rectangular window. Because this window requires no special effort, it is commonly referred to as the no window option. Remember, however, that a window always affects a discrete signal and its spectrum. Let $x[n]$ be a digitized time-domain waveform that has a finite length of $n$. $w[n]$ is a window sequence of $n$ points. The windowed output is calculated as follows:

$$y[n] = x[n] \cdot w[n]$$ \hspace{1cm} (4.3)

If $X$, $Y$, and $W$ are the spectra of $x$, $y$, and $w$, respectively, the time-domain multiplication in the previous equation is equivalent to the frequency domain convolution shown as follows:

$$Y[n] = X[n] * W[n]$$ \hspace{1cm} (4.4)

Convolving with the window spectrum always distorts the original signal spectrum in some way. A window spectrum consists of a main lobe and several side lobes.

The main lobe is the primary cause of lost frequency resolution. When two signal spectrum lines are too close to each other, they might fall in the width of the main lobe, causing the output of the windowed signal spectrum to have only one spectrum line. Use a window with a narrower main lobe to reduce the loss of frequency resolution. A rectangular window has the narrowest main lobe, so it provides the best frequency resolution.

The side lobes of a window function affect frequency leakage. A signal spectrum line leaks into the adjacent spectrum if the side lobes are large. Once again, the leakage results from the convolution process. Select a window with smaller side lobes to reduce spectral leakage. Unfortunately, a narrower main lobe and smaller side lobes are mutually exclusive. For this reason, selecting a window function is application dependent.


(1) The $N$-term Hanning window is defined by the equation
(2) The $N$-term Hamming window is defined by the equation

$$w[n] = 0.5 + 0.5 \cos \frac{2\pi n}{N-1}$$  \hspace{1cm} (4.5)$$

(3) The $N$-term Blackman window is defined by the equation

$$w[n] = 0.54 + 0.46 \cos \frac{2\pi n}{N-1} + 0.08 \cos \frac{4\pi n}{N-1}$$  \hspace{1cm} (4.6)$$

(4) The $N$-term Kaiser window is defined by the equation

$$w[n] = \frac{I_0 \left[ \beta \sqrt{1 - \left( \frac{2n}{N-1} \right)^2} \right]}{I_0[\beta]}$$  \hspace{1cm} (4.7)$$

$I_0(x)$ is the so-called zero order modified Bessel function of the first kind, defined by

$$I_0(x) = 1 + \sum_{j=1}^{\infty} \left[ \frac{(x/2)^j}{j!} \right]^2$$  \hspace{1cm} (4.8)$$

The shape of a Kaiser window is determined by the parameter $\beta$ in the equation for $w[n]$, which is estimated according to the stop band requirements.

### 4.2.3 Theory of Filter

Filtering is one of the most commonly used signal processing techniques. Signal conditioning systems can filter unwanted signals or noise from the signal you are measuring. Filters are systems that change a signal by altering its frequency characteristics in a specific way. Common categories of filters include low pass, high pass, band pass, and band stop. Each filter type has a unique effect on an input signal. Low pass filters tend to smooth signals by averaging out sudden changes. High pass filters, on the other hand, tend to emphasize sharp transitions. Signal filtering can be accomplished using either analog filters or digital filters [11].
Digital filters are widely used in processing digital signals of many diverse applications. One class of digital filters, the linear shift-invariant (LSI) type, is the most frequently used because they are simple to analyze, design, and implement. LSI digital filters are of two main types: Finite Impulse Response (FIR) filters for which the impulse response $h(n)$ is non-zero for only a finite number of samples, and Infinite Impulse Response (IIR) filters for which $h(n)$ has an infinite number of non-zero samples. In the FIR case, the samples of the sequence $h(n)$ are commonly referred to as the filter coefficients; for the IIR case, the filter coefficients include feedback terms in a difference equation [12].

1. Finite Impulse Response (FIR) Filter

Finite impulse response filters, also known as nonrecursive filters, rely only on past input information, never on past output information. They represent a special case of the general difference equation. For a FIR filter, the difference equation and its $z$ transform expression take the form:

$$y[n] = \sum_{k=0}^{M} b_k x[n-k]$$

$$H(z) = \sum_{k=0}^{M} b_k z^{-k}$$

Because each new filter output $y[n]$ does not rely on previous outputs, the impulse response for a nonrecursive filter is guaranteed to have a finite number of terms. The impulse response is

$$h[n] = \sum_{k=0}^{M} b_k \delta[n-k]$$

It consists of $M+1$ impulse functions, weighted by the coefficients $b_k$. Because this filters have finite impulse responses, they are frequently known as finite impulse response (FIR) filters.

2. Infinite Impulse Response (IIR) Filter

Mathematically, an IIR digital filter assumes the following form:

$$y[n] = \frac{1}{a_0} \left( \sum_{k=0}^{M} b_k x[n-k] - \sum_{k=1}^{N} a_k y[n-k] \right)$$

The current filter output $y[n]$ depends on the current and previous values $x[n-k]$ and previous output $y[n-k]$. If $y[n] \neq 0$, its effect on the subsequent
points persists indefinitely. For these reasons, these filters are called infinite impulse response filters.

Filters implemented directly using the structure Equation (4-13) defines are known as direct-form IIR filters. Direct-form implementations are often sensitive to errors introduced by coefficient quantization and by computational precision limits. Also, a filter designed to be stable can become unstable with increasing coefficient length, which is proportional to filter order.

A less-sensitive structure can be obtained by breaking up the direct-form transfer function into lower-order sections, or filter stages. The direct-form transfer function of the filter given by Equation (4-13) (with \( a_0 = 1 \)) can be written as a ratio of \( z \) transforms, as follows:

\[
H(z) = \frac{\sum_{k=0}^{M} b_k z^{-k}}{1 + \sum_{k=1}^{N} a_k z^{-k}}
\]  

(4.14)

The IIR filters provided in the LabWindows/CVI Advanced Analysis Library are derived from analog filters. There are four major types of IIR filters:

- Butterworth filters
- Chebyshev filters
- Inverse Chebyshev filters
- Elliptic filters

4.3 Introduction of DAQ and Data Processing Module

1. Monitoring of Structure Status

In the paper, the cable, girder, and tower of stayed cable bridge are primary objects of monitoring, so user interfaces are designed for the three objects respectively in the panel. Through these objects are different, the operation and functions they have are same or similar. So every user interface, which is shown in Fig.4.3, has the same controls and layout. The user interface
consists of four areas, which are Setting area, PSD Analysis area, Operation area, and Display area. Operating on the user interface can let us to acquire data, analyze data with PSD and display data.

Figure 4.3 The User Interface of Structure Status Monitoring

2. Loads Monitoring

Figure 4.4 The User Interface of Load Monitoring
The main loads on stayed cable bridge are wind load, temperature load, humidity load, and so on. In the paper, the temperature, wind speed, humidity, and ground shake are primary objects of monitoring. Because the operation and functions they have are same or similar, for every user interface, which is shown in Fig.4.4, has the same controls and layout. The user interface consists of four areas, which are Setting area, Operation area, Characteristic Values area, and Display area.

3. Configuring Data Acquisition

![Figure 4.5 The User Interface of Configuring Data Acquisition](image)

Before acquiring data, users should configure some parameters of DAQ firstly, such as sample channel, samples number, and sampling rate. Operating on the user interface shown in Fig.4.5 can let users choose and set these parameters.

4. Filters Selection and Configuring Filter

![Figure 4.6 The User Interface of Digital Filter](image)

After acquiring data, users usually filter the collected data by using some filters. Operating on the user interface shown in Fig.4.6 can let users choose and configure filters. The user interface consists of three areas, which are
Operation area, Configuring Infinite Impulse Response (IIR) filter, and Configuring Finite Impulse Response (FIR) filter.

The main functions of the user interface are:

(1) Choosing whether to use filter.
(2) Choosing which kind of filters should be used.
(3) Configuring Infinite Impulse Response (IIR) filter.
(4) Configuring Finite Impulse Response (FIR) filter.

### 4.4 Experiment Demonstration and Conclusions

To evaluate the application applicability of the module of data acquisition and processing, a DAQ experiment was carried out in the laboratory. Through the experiment, main functions of the DAQ & Processing module including data acquisition, data storage, data display, filtering signal, windowing and power spectrum analysis, are verified.

![Figure 4.7 NI connector accessory BNC-2120](image)

![Figure 4.8 The computer with NI PCI-6023E and BNC-2120](image)
As shown in Fig.4.7 and Fig.4.8, NI connector accessory BNC-2120 is on the computer case, in which the NI DAQ card PCI-6023E has been fixed. Through these equipments, the noise signals were transported from the signal source into the computer.

4.4.1 Demonstration

In the experiment, six cases of operation were set to verify the main functions.

Case 1: At the beginning, DAQ parameters were set according to what Fig.4.9 shows, the number 4 channel was selected, and the number of samples and sample rate are 1024 and 2000 respectively. There are several peaks clearly shown in the power spectrum plot in Fig.4.10.

![Figure 4.9 Basic DAQ parameters](image)

![Figure 4.10 The user interface of case 1](image)

Case 2: Base on case 1, window and average time were adopted. The window type was flat top, and average time was set to be 50. Then the power spectrum waveform became to be smoother than the previous one.
Figure 4.11 The user interface of case 2

Figure 4.12 Selecting IIR low pass filter with cutoff frequency 600Hz

Figure 4.13 The user interface of case 3
Case 4: Base on case 1, the samples number 1024 was replaced by 2048. Because of the reason, just as what Fig. 4.14 is showing, the power spectrum plot looks more precise and peaks are sharper.

Figure 4.14 The user interface of case 4

Figure 4.15 Selecting FIR high pass filter with cutoff frequency 500Hz

Figure 4.16 The user interface of case 5
Case 5: Based on case 4, as shown in Fig. 4.15, a FIR high pass filter with the cutoff frequency 500Hz was adopted. So the waveform of lower than 500Hz shown in Fig. 4.16 is filtered out.

![Image](image1.png)

**Figure 4.17 The user interface of case 6**

Case 6: Based on case 4, Hamming window and average time were adopted. The same as case 2, the power spectrum waveform became to be smoother.

### 4.4.2 Conclusions

From the experiment of running the module of data acquisition and processing for aforementioned six cases, we can see that:

1. The module can be used to acquire data continuously and fluently in terms users’ requirements.
2. The module can be used to do the real-time power spectrum analysis.
3. The module affords many kinds of filter and windows which can be conveniently adopted in processing data by users.
5 The Monitoring of Cable Force

Since cables are a crucial element for overall structural safety of the structure, the accurate measurement of cable tension force has practical importance to not only a construction stage but also a maintenance stage. Currently available techniques to estimate the cable tension include the static methods directly measuring the tension by a load cell or a hydraulic jack, and the vibration methods indirectly estimating the tension from measured natural frequencies [13]. In practice, the vibration methods have received increasing attention because of its simplicity and speediness.

Instead of direct measurement of cable forces, vibration-based methods have been most widely used in the estimation of cable tension forces. The cable vibrations excited by either ambient or manual sources are first measured and the cable vibration frequencies are identified accordingly. Cable tensions can then be indirectly calculated from the measured cable frequencies using the relationship between cable tensions and their corresponding natural frequencies.

In the section, the string vibration theory firstly is introduced. Considering cable’s sag and bending stiffness effects, we will discuss the practical formulas for the calculation of cable force. At last, the design of monitoring cable force is described, which includes the user interface, program and operation.

5.1 Vibration Methods

5.1.1 String Vibration Theory

One assumed ideal cable with $\rho$ the unit length mass and $EI$ the flexural rigidity is loaded with the cable tension $T$. In the case of neglecting sag, the rigidity and the cable tension force along the cable axis can be considered to be changeless.

Supposing the vibration of cable at arbitrary point in axis $x$ is always vertical, then $y$ the displacement of cable is the function depending on $x$ and $t$ the time described by:

$$y=y(x, t)$$

(5.1)
When the cable is vibrating along the direction y with tiny amplitude, the mass of the differential cable element is

$$\rho ds = \rho \sqrt{(dx)^2 + (dy)^2} \approx \rho ds$$  \hspace{1cm} (5.2)$$

On $dx$ the differential element, which is shown in Fig.5.1, there are $T$ the tension, $-\rho dx \frac{d^2y}{dx^2}$ the inertial-force, $M$ the moment, $Q$ the shearing force, and the load $q(x,t)$.

![Figure 5.1 Differential element of ideal cable](image)

At one moment $t$, the inclined angle at $x$ and $x+dx$ are $\theta(x,t)$ and $\theta + \frac{\partial \theta}{\partial x} dx$ respectively, and when the differential element moves in the direction y, according the Newton’s second law, the dynamic equation is

$$\rho dx \frac{\partial^2 y}{\partial t^2} = T \left( \theta + \frac{\partial \theta}{\partial x} dx \right) + Q + \frac{\partial Q}{\partial x} dx - T \theta - Q - q dx$$  \hspace{1cm} (5.3)$$

The inclined angle at $x$ can be expressed as

$$\theta(x,t) = \frac{\partial y(x,t)}{\partial x}$$  \hspace{1cm} (5.4)$$

Therefore equation (5-3) is:

$$\rho dx \frac{\partial^2 y}{\partial t^2} = T \frac{\partial^2 y}{\partial x^2} + \frac{\partial Q}{\partial x} - q$$  \hspace{1cm} (5.5)$$
Considering the balance of moments at \( x+dx \) gives:

\[
M + \frac{\partial M}{\partial x} dx - M + Q dx + q \frac{dx}{2} dx = 0
\]  

(5.6)

Neglecting the high order part, we can get:

\[
\frac{\partial M}{\partial x} = -Q
\]  

(5.7)

From the bend theory in the Material Mechanics, the known equation is:

\[
EI \frac{\partial^2 y}{\partial x^2} = M
\]  

(5.8)

Inserting equations (5.7) and (5.8) into equation (5.5) gives:

\[
\rho \frac{\partial^2 y}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} - T \frac{\partial^2 y}{\partial x^2} + q = 0
\]  

(5.9)

If the load is zero, we get

\[
\rho \frac{\partial^2 y}{\partial t^2} + EI \frac{\partial^4 y}{\partial x^4} - T \frac{\partial^2 y}{\partial x^2} = 0
\]  

(5.10)

For the cable without the flexural rigidity, equation (5.10) can be simplified as

\[
\frac{\partial^2 y}{\partial t^2} = C^2 \frac{\partial^2 y}{\partial x^2}
\]  

(5.11)

where \( C = T / \rho \) is the wave speed along the cable axis.

For the pined cable, the solution for equation (5.11) is

\[
T = \frac{4 \rho l^2 f_n^2}{n^2}
\]  

(5.12)

in which \( T \) is the cable force, \( \rho \) is the unit length mass of cable; \( l \) is the length of cable; \( n \) is the order of frequency; \( f_n \) is the n-order natural frequency of cable.

So, for one given cable whose \( \rho \) and \( l \) are also known, we can get the cable force \( T \) as soon as the n-order natural frequency is measured.

Specially, when we use the fundamental frequency which is the first order natural frequency, the final solution becomes
For the actual cable, parameters such as rigidity, sag, and boundary condition should be considered. But with the cable length increasing, these factors have less influence. From equation (5.12), the following two deductions can be got:

\[ f_n - f_{n-1} = n \sqrt{\frac{T}{4 \rho l^2}} - (n-1) \sqrt{\frac{T}{4 \rho l^2}} = \sqrt{\frac{T}{4 \rho l^2}} = f_1 \]  

(5.14)

from which it can be seen that each order of frequency is distributed at the same interval and the interval is just equal to the fundamental frequency. Therefore, the difference between high order frequencies makes it possible to acquire the fundamental frequency and then obtain the cable force by using the equation (5.13). Furthermore, if \( A \) the cross section area of cable is given, the stress in the direction of cable axis can be calculated by the following equation:

\[ \sigma = \frac{T}{A} = \frac{4 \rho l^2 f_1^2}{A} \]  

(5.15)

In practical application, the measured result of stress is compared with the axial stress intensity of cable, and then the user can evaluate the real status of cable.

5.1.2 Estimating Cable Force with Practical Formulas

The simplest relationship to calculate the cable forces based on string vibration frequencies is so called chord equation where the cables are idealized as taut strings. This idealization simplifies the analysis but may cause unacceptable errors in many situations since the cable sag and bending stiffness effects are neglected. The taut-string formula should be modified by taking into account cable’s sag and bending stiffness effects [14].

Because of the above-mentioned reason, practical formulas to estimate the cable forces from measured frequencies were proposed by Zui et al. where the first and second natural frequencies of cable vibration are needed [15].
Under the assumption of fixed-end boundary conditions, Zui et al. derived a set of practical formulas in the aim that field engineers can quickly and directly calculate cable forces. Zui et al. introduced dimensionless parameters $\xi$ and $\Gamma$, which show the properties of the cable, presenting the flexural rigidity and sag, respectively, and used the single mode to estimate the cable tension force. In the region where the effects of cable sag and dynamic tension are large, the value of cable force is very sensitive to the

| $\Gamma \geq 3$ | $T = 4\rho(f_1l)^2 \left[0.828 - 10.5 \left(\frac{c}{f_1}\right)^2\right]$ | $0 \leq \xi \leq 6l$ | 1 |
| $\Gamma \leq 3$ | $T = 4\rho(f_1l)^2 \left[0.865 - 0.55 \left(\frac{c}{f_1}\right)^2\right]$ | $6 \leq \xi \leq 17$ | 2 |
| $\Gamma \geq 3$ | $T = 4\rho(f_1l)^2 \left[1 - 2.2 \frac{c}{f_1} - 0.55 \left(\frac{c}{f_1}\right)^2\right]$ | $17 \leq \xi$ | 3 |
| $\Gamma \leq 3$ | $T = \rho(f_2l)^2 \left[0.882 - 85 \left(\frac{c}{f_2}\right)^2\right]$ | $0 \leq \xi \leq 17$ | 4 |
| $\Gamma \geq 3$ | $T = \rho(f_2l)^2 \left[1 - 6.33 \frac{c}{f_2} - 1.58 \left(\frac{c}{f_2}\right)^2\right]$ | $17 \leq \xi \leq 60$ | 5 |
| $\Gamma \leq 3$ | $T = \rho(f_2l)^2 \left[1 - 4.4 \frac{c}{f_2} - 1.1 \left(\frac{c}{f_2}\right)^2\right]$ | $60 \leq \xi$ | 6 |

$$c = \sqrt{\frac{EI}{\rho l^4}}, \xi = \sqrt{\frac{T}{EI}}, \delta = \frac{s}{l_0}, l_0 = l \cdot \cos \theta$$

$$\Gamma = \frac{\rho gl}{\sqrt{128EA}} \left(\frac{0.31\xi + 0.5}{0.31\xi - 0.5}\right)$$

$A$ the cross sectional area, $\theta$ the inclination, $\delta$ the sag-to-span ratio
$s$ the sag, $l_0$ the horizontal length of cable
change of first-order natural frequency. This means that the slight measurement error of natural frequency causes a large error of cable force. On the other hand, even in this region, the effects of cable sag and dynamic tension are negligibly small for second-order mode, and the value of cable force is not so sensitive to the change of second-order natural frequency. Therefore, for the region where cable sag effect is dominant and namely the value of $\Gamma$ is small, it is desirable to use second-order mode for the measurement of cable forces. On the contrary, in the region of small effects the first-order mode is used because, in this region, the effects of cable sag and inclination are negligibly small even for first-order mode and it is easier to excite a cable in first-order mode than in second-order mode. The formulas are concisely described in the above table 5.1.

5.2 Introduction of the Cable Force Monitoring Module

In the system, both string vibration theory and Zui’s practical formulas are applied. The former one is used in the main panel, where the saved data of fundamental frequency and calculated cable force are displayed. If we have interest in the cable force at one moment or when we feel that the cable’s status is abnormal, we may urgently want to get more accurate value. Then we can use the Accurate Calculate panel based on Zui’s practical formulas to get the result we care. The operation flow chart is shown by Fig.5.2.

![Figure 5.2 The operation flow chart](image-url)
On the main panel shown in Fig. 5.3, the user interface consists of three parts, which are Operation Area, Setting Parameters and Display Data and Results.

On the main panel, we can get some basic information about the cable status from the waveform plot of cable force shown in the screen. However, we sometimes want to know the more accurate result to evaluate and
analyze the cable better. In this case, the Accurate Calculation panel is needed. The Fig.5.4 is showing the user interface of Accurate Calculation.

![Flow Chart of Accurate Calculation](image)

**Figure 5.5 Flow Chart of Accurate Calculation**

After giving all needed parameters, the calculation based on practical formulas listed in table 5.1 starts. The process of the calculation can be described by the following flow chart.

From the above figure we can see that given parameters are inserted into formula 1 firstly. After getting results including cable force $T$, dimensionless parameters $\xi$ and $\Gamma$, $\xi$ and $\Gamma$ will be judged to ensure whether their values accord with conditions of adopting formula 1. If the answer is “Yes”, results are shown as final results in the user interface, otherwise given parameters are inserted into formula 2 to calculate. In the same way, every formula will be adopted orderly until the result according with conditions appears.

### 5.3 Demonstration and Conclusions

#### 5.3.1 Demonstration

To verify the applicability of the module, two virtual cables are analyzed. The physical and geometric parameters of the two cables are listed in Table 5.2.

Above all the data is loaded through selecting the data file in File Select Popup shown in Fig.5.6. And then geometric parameters are input in Setting Parameters area shown in Fig.5.7.
Table 5.2 Parameters of two cables*

<table>
<thead>
<tr>
<th>Cable</th>
<th>$\rho$ (kg/m)</th>
<th>$l$ (m)</th>
<th>$E$ (N/m²)</th>
<th>$I$ (m⁴)</th>
<th>$\theta$ (rad)</th>
<th>$A$ (m²)</th>
<th>Sag (m)</th>
<th>$f_1$ (Hz)</th>
<th>$f_2$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.8</td>
<td>76.4</td>
<td>1.83e11</td>
<td>4.57e-6</td>
<td>0.5408</td>
<td>0.006</td>
<td>0.088</td>
<td>1.732</td>
<td>3.461</td>
</tr>
<tr>
<td>2</td>
<td>47.8</td>
<td>126.4</td>
<td>1.83e11</td>
<td>5.00e-6</td>
<td>0.4536</td>
<td>0.006</td>
<td>0.52</td>
<td>0.769</td>
<td>1.499</td>
</tr>
</tbody>
</table>

*: From one article “Cable Force Analysis of Gi-Lu Cable-Stayed Bridge after Gi-Gi Earthquake”

Figure 5.6 Load Data

Figure 5.7 Input Parameters

After clicking the button Display, the waveform of loaded data and got cable force are displayed on graph Fundamental Frequency and Cable Force respectively, just like what is being shown in Fig.5.8.

Figure 5.8 Display waveform plots of loaded data and cable force
Then the physical and geometric parameters of two cables are input in Accurate Calculation panel orderly to get accurate results. Input parameters and got results of two cables are shown in Fig.5.9 and Fig.5.10 respectively.
**Table 5.3 Comparison of computed cable force**

<table>
<thead>
<tr>
<th>Cable</th>
<th>String Theory</th>
<th>Zui’s Practical Formulas</th>
<th>Number of Used Formula</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.3479e6</td>
<td>3.2512e6</td>
<td>3</td>
<td>2.89%</td>
</tr>
<tr>
<td>2</td>
<td>1.8065e6</td>
<td>1.6723e6</td>
<td>6</td>
<td>7.43%</td>
</tr>
</tbody>
</table>

The table 5.3 lists computed results by using string theory and Zui’s practical formulas and the relative error between them.

### 5.3.2 Conclusions

The cable force monitoring module can not only carry out the calculation of cable force according string theory, but also have the calculation ability of getting more actual and accurate results by adopting Zui’s practical formulas.

From table 5.3 we can see that results computed by using string theory are obviously larger than that computed by using Zui’s practical formulas, and the longer the cable is, the error between them is larger. So in real application, for the long cable, Zui’s practical formulas is the better choice.
The Damage Detection for the Girder Based on GA

The girder is the most important component of the stayed cable bridge. So the damage detection for the girder certainly is the essential part for the structural health monitoring system.

Correlation-based methods have been widely employed for damage detection. One of the earliest attempts is to use the correlation of the natural frequencies. Messina et al. proposed the DLAC (damage location assurance criterion) [16] which is similar to the concept of a MAC (modal assurance criterion). Later, they further developed the MDLAC (multiple damage location assurance criterion) [17] that accommodates multiple damage locations. The advantage that the MDLAC offers over the DLAC is that the sensitivity matrix is incorporated into the correlation equation. By including the derivatives of the natural frequencies with respect to the damaged parameters, the correlation problem evolves into an optimization problem, which can be efficiently solved with Genetic Algorithms.

Genetic Algorithms (GA) has been one of the most successful search algorithms since its advent in 1970s [18]. Essentially, GA follows the theories of Darwin governing the biological world to solve optimization problems.

In this paper, the damage detection for the girder of the stayed-cable bridge will adopt the MDLAC (multiple damage location assurance criterion) that exploit the correlation of natural frequencies. To avoid performing an exhaustive search of the parameter space, GA is adopted to rapidly and efficiently identify multiple damage locations using only natural frequencies [19]. Local damage is modeled as a reduction of the Young’s modulus of particular combinations of elements in the structural model.

6.1 Theories of Structure Damage Detection

6.1.1 Single damage detection using natural frequencies

Determining the level of correlation between the measured and predicted (hypothesis) modal frequencies provides a simple statistical tool for locating damage. The parameter vectors used for evaluating correlation
coefficients consist of the first n modal frequency changes due to damage to the modal frequencies, i.e., $\Delta f = f_h - f_d$. Here, $f_h$ and $f_d$ denote the natural frequency vectors of the healthy and damaged structures, respectively. Likewise the corresponding hypothesis vector, predicted from an analytic model is denoted $\{\delta f\}$. Given a pair of parameter vectors, one can estimate the level of correlation in several ways. The easiest way to estimate correlation is to calculate the angle between the two parameter vectors. A damage localization method using the pair comparison tries to find linear correlation of modal frequency variation vectors, as in

$$C_j = \frac{\{\Delta f\}^T \{\delta f_j\}}{|\{\Delta f\}| \cdot |\{\delta f_j\}|} \quad (6.1)$$

Here, the subscript $j$ indicates the hypothesized location of damage ($j = 1, 2, \ldots, r$). Another correlation-based metric called the damage location assurance criterion (DLAC) is expressed in the following form:

$$DLAC(j) = \frac{|\{\Delta f\}^T \cdot \{\delta f_j\}|^2}{|\{\Delta f\}^T \cdot \{\Delta f\}| \cdot |\{\delta f_j\}^T \cdot \{\delta f_j\}|} \quad (6.2)$$

As can be seen from the Cauchy Schwarz inequality, DLAC values lie in the range of 0 to 1, with 0 indicating no correlation and 1 indicating an exact match between the patterns of frequency changes. The location $j$ giving the highest DLAC value gives the best match to the measured frequency change pattern and is therefore taken as the predicted damage site.

### 6.1.2 Multiple damage detection using natural frequencies

The DLAC formulation employing natural frequencies is in general only capable of detecting a single damage location. Because a unique pattern of modal frequency changes only holds for a single damage case, the algorithm becomes impractical for structures that have multiple defects, or an unknown number of defects. But it also can be extended to multiple sites by making use of an analytical model of the structure.

The model is based on the sensitivity of the frequency of each mode to damage in each location. To calculate the sensitivities, it is assumed that damage to the $j$th element is simulated by a homogeneous reduction of
stiffness, but with no change of mass. In this case, the sensitivity of the \( k \)th natural frequency to damage at location \( j \) is given by equation (6.3) below.

\[
\frac{\partial f_k}{\partial D_j} = \frac{1}{8 \cdot f_k^0 \cdot \pi^2} \left[ \begin{bmatrix} \phi_k^0 \end{bmatrix}^T \begin{bmatrix} K_j^0 \end{bmatrix} \begin{bmatrix} \phi_k^0 \end{bmatrix} \right]
\]

(6.3)

where \([K_j^0]\) is the stiffness matrix of the \( j \)th element positioned within the global matrix, \([M^0]\) is the global mass matrix and \( \{ \phi_k^0 \} \) is the \( k \)th mode shape vector; all terms evaluated are for the undamaged structure.

A stiffness reduction factor \( D_j \) for the element is introduced such that \( D_j = 1 \) for no damage and \( D_j = 0 \) for complete loss of the element (100% damage). For any combination of size and location of damage at one or more sites (embodied in a vector of changes to individual stiffness reduction factors \( \{ \delta D \} \)), it is assumed that the corresponding reductions in the natural frequencies can be written using a linear combination of the sensitivities in the form:

\[
\delta f_i = \frac{\delta f_i}{\delta D_1} \delta D_1 + \frac{\delta f_i}{\delta D_2} \delta D_2 + \cdots + \frac{\delta f_i}{\delta D_m} \delta D_m
\]

\[\text{......}\]

\[
\delta f_p = \frac{\delta f_p}{\delta D_1} \delta D_1 + \frac{\delta f_p}{\delta D_2} \delta D_2 + \cdots + \frac{\delta f_p}{\delta D_m} \delta D_m
\]

or

\[
\{ \delta f \} = \begin{bmatrix} \frac{\partial f_1}{\partial D_1} & \cdots & \frac{\partial f_1}{\partial D_m} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_p}{\partial D_1} & \cdots & \frac{\partial f_p}{\partial D_m} \end{bmatrix} \{ \delta D \}
\]

(6.4)

or

\[
\{ \delta f \} = [S] \{ \delta D \}
\]

Equation (6.4) gives the analytical predictions of the frequency changes, \( \{ \delta f \} \), resulting from an arbitrary pattern of damage defined by the vector \( \{ \delta D \} \). Substituting this into equation (6.2), one obtains a statistical correlation with the measured frequency changes, \( \{ \Delta f \} \). This is termed the Multiple Damage Location Assurance Criterion (MDLAC) since it is a function of all elements in the damage vector \( \{ \delta D \} \).
Using the same damage detection principle as before, the required damage state is obtained by searching for the vector \( \{\delta D\} \) which maximizes the MDLAC value. The search is initiated by setting the damage vector \( \{\delta D\} \) to \( \{0.01\%\} \). This is chosen to be close to, but not at, the undamaged state since \( \{\delta D\} = \{0\} \) is a singular point for equation (6.5).

The only difference between the previously discussed correlation methods and the MDLAC is the presence of the sensitivity matrix. Although incorporating the sensitivity matrix into the correlation expression enables the identification of multiple damage locations, it also introduces challenges in finding the appropriate combination of damage variables \( \delta D \). The objective is to find a damaged variable vector \( \{\delta D\} \) that makes the MDLAC equal to one. However, evaluating all possible combinations of damage variables that maximizes the MDLAC is prohibitive even for a simple problem. For example, considering an identifiable model having 10 damage locations (elements) with five possible levels of damage severity produces \( 5^{10} \) potential combinations of damage variables. Thus, an efficient searching algorithm such as GA is needed to determine the correct set of damage variables.

### 6.2 Genetic algorithms

GA exploits the mechanisms of biological evolution to perform optimization without information regarding the derivative of the objective function. The search strategy in GA is based on survival of the fittest; the global optimum can be sought by evolution in a series of generations. The initial population or trial set of solutions (chromosomes) repeatedly evolve throughout generations until convergence to a desired solution occurs. The key actions in GA are encoding, selection, crossover, and mutation. The following is the Outline of the Basic Genetic Algorithms. The flow chart of solution steps of GA is in Fig.6.1.
1. Start: Generate random population of n chromosomes (suitable solutions for the problem)

2. Fitness: Evaluate the fitness \( f(x) \) of each chromosome \( x \) in the population

3. New population: Create a new population by repeating following steps until the new population is complete

   [1] Selection: Select two parent chromosomes from a population according to their fitness (the better fitness, the bigger chance to be selected)

   [2] Crossover: With a crossover probability cross over the parents to form a new offspring (children). If no crossover was performed, offspring is an exact copy of parents.


   [4] Accepting: Place new offspring in a new population

4. Replace: Use new generated population for a further run of algorithm

5. Test: If the end condition is satisfied, stop, and return the best solution in current population

---

**Figure 6.1 Flow chart of solution steps of GA**
6. Loop: Go to step 2

6.3 Illustrative Application

In this section, the performance of adopting the Genetic Algorithms for locating damage based on the damage detection algorithms using modal sensitivity and correlation through a simple numerical example is demonstrated. In the process, the number of damaged elements and their stiffness reduction represent the damage locations and damage ratio.

6.3.1 Making Model

The model is a simply supported beam having 10 elements as shown in Fig.6.2. The length, thickness and width are 1m, 0.01532m and 0.036m, respectively. The Young’s modulus E=2.1×10¹¹N/m², density \( \rho = 1800\text{kg/m}^3 \) and Poisson ratio \( \nu = 0.3 \).

![Figure 6.2 Simply supported beam](image)

According to the equation 6.3, \([\mathbf{K}_j^0], [\mathbf{M}^0], \{ \phi_k^0 \} \) and \( f_k \) should be derived firstly. By inserting all of given parameters and known results into the equation 6.3, we can get the sensitivity of the \( k \)th natural frequency to damage at location \( j \). Finally, the sensitivity matrix of the model is calculated, the result is:

\[
[S] = \begin{bmatrix}
1.38 & 5.75 & 12.72 & 10.11 & 2.83 & 1.13 & 1.17 & 6.09 & 23.53 & 58.2 \\
5.51 & 24.42 & 8.66 & 2.52 & 26.3 & 66.28 & 39.84 & 5.26 & 8.11 & 67.74 \\
13.74 & 23.45 & 4.14 & 65.4 & 54.13 & 1.61 & 55.09 & 58.88 & 2.02 & 66.77 \\
23.44 & 15.27 & 53.37 & 60.3 & 17.75 & 90.62 & 2.36 & 81.69 & 33.65 & 61.06 \\
32.35 & 1.19 & 107.84 & 2.54 & 99.66 & 10.57 & 90.76 & 24.16 & 77.98 & 60.31
\end{bmatrix}
\] (6.6)
6.3.2 Damage Simulation

In the paper, the identified damage variables are expressed in ratios of Young’s modulus (E) reduction, and the damage will be introduced at the selected elements. 0 represents that the Young’s modulus reduction is zero; 0.1 represents that the Young’s modulus reduction is 10%; 0.2 represents that the Young’s modulus reduction is 20%. In the same way, the damage vector \([0,0.2,0,0.3,0,0.4,0,0,0,0]\) represents: the Young’s modulus reduction is 20% at element 2; the Young’s modulus reduction is 30% at element 5; the Young’s modulus reduction is 40% at element 7.

The following four damage cases of simulation are:

1. The Young’s modulus reduction is 40% at element 4. The simulation damage vector is \([0,0,0,0.4,0,0,0,0,0,0]\).

2. The Young’s modulus reductions are 20% and 30% at element 2 and element 7 respectively. The simulation damage vector is \([0,0.2,0,0,0,0,0.3,0,0,0]\).

3. The Young’s modulus reductions are 30% and 40% at element 4 and element 9 respectively. The simulation damage vector is \([0,0,0,0.3,0,0,0,0,0,0.4,0]\).

4. All the Young’s modulus reductions are 30% at element 2, element 5 and element 9 respectively. The simulation damage vector is \([0,0.3,0,0,0.3,0,0,0,0.3,0]\).

According to the equation (6.4), we can get the natural frequency changes of above-mentioned simulation damage cases as shown in table 6.1.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Case 1 $\Delta f_1$</th>
<th>Case 2 $\Delta f_2$</th>
<th>Case 3 $\Delta f_3$</th>
<th>Case 4 $\Delta f_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Case 2</td>
<td>12.4434 4.0032 20.4271 31.5507 31.9551</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The objective of the next step is to find a damaged variable vector that makes the MDLAC equal to one. However, evaluating all possible combinations of damage variables that maximizes the MDLAC is prohibitive even for our simple problem. In our problem, the model having
10 damage locations (elements) with five possible levels of damage severity produces $5^{10}$ potential combinations of damage variables. Thus, an efficient searching algorithm GA is needed to determine the correct set of damage variables.

### 6.3.3 Solution steps of GA

The population size for each generation is set to be 20. One individual represents one damage vector, in which the ratios of Young’s modulus reduction can be seen as chromosomes. Main solution steps include generating the initial population, calculation of fitness, and generating new population which consists of the selection, crossover and mutation. After calculation, the individual with the best fitness will be output as the result.

1. Generate the initial population

   Every individual of the initial population consists of random chromosomes, which means that every code generated by equiprobably selecting number in \{0, 0.1, 0.2, 0.3, 0.4\}.

2. Calculation of fitness

   For the problem, the equation (6.5) is used as the fitness function. We can get the fitness of every individual as long as we inserting it into the fitness function. And then we will select the individual with the best fitness and save it as “best fit individual”. If one other individual has the better fitness in new population, it will become new “best fit individual” replacing the old one.

3. Generate new population

   (1) Selection

   Based on the roulette wheel selection, two parents are selected from present population according to their fitness. The probability of selecting the individual is:

   $$ P_i = \frac{MDLAC_i}{\sum_{k=1}^{20} MDLAC_k} \quad (i = 1, 2, \cdots, 19, 20) \quad (6.7) $$

   (2) Crossover
The parents are crossed over with a crossover probability to form a couple of new offspring. The steps are described by following:

[1] Equiprobably select one number in 1~10 as the number of crossover point.

[2] According to the number, chromosome strings of the two parents from the beginning to the crossover point are exchanged.

For example: Two parents are:

Parent 1 [0.2, 0.3, 0, 0.2, 0, 0, 0.1, 0, 0.3, 0]
Parent 1 [0, 0.3, 0.1, 0, 0.3, 0.4, 0, 0.1, 0, 0]

If the number of crossover point is 4, the offspring are:

Offspring 1 [0, 0.3, 0.1, 0, 0, 0.1, 0, 0.3, 0]
Offspring 2 [0.2, 0.3, 0, 0.2, 0.3, 0.4, 0, 0.1, 0, 0]

(3) Mutation

We mutate new offspring with a mutation probability at each locus (position in chromosome). To selected position, one value equiprobably selected in {0, 0.1, 0.2, 0.3, 0.4} replaces the original value.

For example: Mutating above offspring 2.

Offspring 2 [0.2, 0.3, 0, 0.2, 0.3, 0.4, 0, 0.1, 0, 0]

If position 4 and 7 are selected, after mutation the new offspring 2 may be:

Offspring 2 [0.2, 0.3, 0, 0.1, 0.3, 0.4, 0.4, 0.1, 0, 0]

(4) Accepting

Placing new offspring instead of parents in the population generates the new population.

4. Go to the step 2 and check whether the “best fit individual” is satisfied. If the result is satisfied, the “best fit individual” is output as the final solution. Otherwise repeat the process.

6.4 Demonstration and Conclusions

6.4.1 Description of user interface

The user interface of damage detection module, shown in Fig.6.3, consists
of three parts which are Input Parameters area, Operation area and Display Result area. In Input Parameters area, users can input the sensitivity matrix and natural frequency changes used in MDLAC, and set the crossover probability and mutation probability used in the calculation of GA.

![User interface of damage detection](image)

**Figure 6.3 User interface of damage detection**

Buttons in Operation area are used to control the process of calculation. Every numeric tank control in Display Result area represents one element of the bridge, and its showing number is equivalent to the ratio of Young’s modulus reduction. This means that the arrangement of numeric tanks indicates the damage vector.

### 6.4.2 Calculations and Discussion

The module of the system is designed based on the theory of MDLAC, but its principle calculation foundation and program heart is genetic algorithms. To verify the applicability of the module, the aforementioned cases of simulation damage are adopted.

In the process of calculation, the crossover probability and mutation probability are set to be 0.1 and 0.01 respectively.
Fig. 6.4 shows the damage localization result for case 1. We can see that the result is exactly equal to the simulation damage vector. This means that the module can locate the single damage perfectly.

Figure 6.4 Result of case 1

Fig. 6.5 and Fig. 6.6 show the damage localization results for case 2 and case 3 respectively. From them we can see that the results, despite are not equal to simulation damage vectors absolutely, indicate the damage location accurately. So, when there are two damage locations, using the module still can accurately and expressly locate damages.

Figure 6.5 Result of case 2
Figure 6.6 Result of case 3

Figure 6.7 Four different results of case 4
Fig. 6.7 shows four different damage localization results for case 4. We can see that any one of them can’t accurately indicate the locations of simulation damage, despite their MDLACs have been over 0.998. I think that there are two main reasons leading to the outcome. First, the model beam only is divided into ten elements; this reduces the accuracy of analysis with multiple damage location. Second, in the demonstration, only five natural frequencies are used, which can’t give us more unique information about modes. Although the final results don’t give us the exact damage locations, we still can get some valuable information. After all, it is obvious that element 5, 7 and 9 have the larger damaged probability.

6.4.3 Conclusions

The subsystem of damage detection for the girder is designed based on the theory MDLAC and Genetic Algorithms, which is an efficient searching algorithm for finding the best solution. Through the above-mentioned demonstration, the subsystem can accurately locate the damage when the damage locations are not more than two. If with three or more damage locations, the subsystem can provide some valuable information, but can’t indicate the accurate position.
7 Data Participation based on DataSocket

7.1 DataSocket Overview

DataSocket [20], both a technology and a group of tools, facilitates the exchange of data and information between an application and a number of different data sources and data targets. These sources and targets include files, HTTP/FTP servers, OLE for Process Control (OPC) servers, and National Instruments DataSocket Servers for publishing live data between applications. Often, these sources and targets are located on a different computer. You can specify DataSocket sources and targets (connections) using URLs (uniform resource locators) that adhere to the familiar URL model.

DataSocket allows you to read data from multiple types of data sources and allows you to transfer rich data between machines as shown in Fig.7.1. DataSocket greatly simplifies this task by providing a unified API for these low-level communication protocols. Transferring data across computers with DataSocket is as simple as using a browser to read Web pages on the Internet.

![Data transfer based on DataSocket](image)

Figure 7.1 Data transfer based on DataSocket

DataSocket consists of two pieces – the DataSocket API and the DataSocket Server. The DataSocket API presents a single interface for communicating with multiple data types from multiple languages. DataSocket Server simplifies Internet communication by managing TCP/IP programming for you.
7.2 Introduction of Data Participation Module

Based on Datascket, two components of the module, Writer and Reader, were built.

Figure 7.2 User interface of Writer

Figure 7.3 User interface of Reader
(1) Writer
The writer panel, which is shown in Fig. 7.2, is used to write data in one data target address and display the data on the graph.

(2) Reader
The reader panel, which is shown in Fig. 7.3, is used to read data from one data target address and display the data on the graph.

7.3 Demonstration and Conclusions

To verify the applicability of functions of the subsystem, three tasks by using DataSocket Writer and DataSocket Reader, which are writing data into one URL address of dstp:, reading data from the URL address and reading data from one URL address of http:, were completed respectively.

7.3.1 Demonstration
(1) Write data
One txt file containing power spectrum data saved by using DAQ module, shown in Fig. 7.4, was selected and loaded. And the power spectrum data were displayed and wrote into the target address dstp://localhost/wave successfully, as shown in Fig. 7.5.

![Figure 7.4 Select and load file](image-url)
(2) Read the data from Writer

We input the same target address as the one in task 1, then the data just promulgated were read and displayed, as shown in Fig. 7.6.
(3) Read data from one http: address

With inputting the address http://www.natinst.com/cworks/datasocket/chirp.dsd, the data in the data file chirp.dsd were read and displayed, as shown in Fig.7.7.

![Figure 7.7 The user interface of DataSocket Reader after reading data from http: address](image)

7.3.2 Conclusions

The subsystem of Data Participation was designed and made by using the Datasocket technology. Through Datasocket technology, the subsystem, which can make users to write data into URL addresses, read and shear data from other data resources, achieves the purpose of data participation.
8 Conclusions

The objective of thesis is to describe the process in structural health monitoring design and researches for stayed-cable bridges by using LabWindows/CVI, and introduce the theories and technologies adopted in the process.

The framework of the monitoring system can be separated into four subsystems which are Structure Status Monitoring, Load Monitoring, Damage Monitoring & Detection and Data Participation. The main objects of structure status monitoring are the girder, the cable and the tower. In load monitoring what we most interest us are the temperature, wind speed, humidity and ground shake. The cable force monitoring and damage detection for the girder are main modules of the damage monitoring & detection.

The monitoring system is provided with four main functions: Data Acquisition, Data Processing & Calculation, Data Storage and Data Communication.

(1) The module of data acquisition can be used to acquire data continuously and swimmingly in terms users’ requirements, do the real-time power spectrum analysis, and it affords many kinds of filter and windows which can be conveniently adopted in processing data by users. In the section, basic knowledge about DAQ system and data processing theories are introduced.

(2) The cable force monitoring module can not only display the waveform plot of cable force according string theory, but also have the calculation ability of getting more actual and accurate results by adopting Zui’s practical formulas. And we find that results computed by using string theory are obviously larger than that computed by using Zui’s practical formulas, and the longer the cable is, the error between them is larger. So in real application, for long cable Zui’s practical formulas is the better choice.

(3) The subsystem of damage detection for the girder is designed based on MDLAC and Genetic Algorithms. The subsystem can accurately locate the damage when the damage locations are not more than two. If with three or more damage locations, the subsystem can provide some valuable information, but can’t indicate the accurate position.
(4) The subsystem of Data Participation was designed and made by using the Datasocket technology. Through Datasocket technology, the subsystem, which can make users to write data into URL addresses, read and shear data from other data resources, achieves the purpose of data participation.

Structural health monitoring for stayed cable bridges is one system engineering with the characteristic of collaborating with various methods and technologies. In this work, some research and useful exploration have been done for building a system based on LabWindows/CVI, but because of the limit from author’s ability and given time, the finished system is far from perfect and many problems need to be studied further. Some suggestions are listed in following:

(1) In structure monitoring and loads monitoring, more monitoring objects can be introduced; for one monitoring object, more characteristic parameters can be shown; more methods for data processing and analysis, such as FRF, can be applied also.

(2) As the development of methods for estimating cable tension force, some new technologies and methods can be applied in the monitoring system.

(3) Studies for damage detection and damage location also have gotten great progress. In applications, applying new methods, for example using different modal parameters to define the damage and using changes of mode shape to locate damage, can improve the accuracy of structural damage detection.

(4) Various data in systems can be managed better with database technologies. To carry out the aim, LabWindows/CVI itself providing some relational tools is one choice, and another way, which may be the better choice, is that the database management module developed in Visual Basic or Visual C++ is inserted into the system.

(5) Developing the data display module based on Web technology can make users get and find data easier and more conveniently.

Above mentions only are a few aspects for updating the system. After all, developing one whole monitoring system with all needed functions is a complicated engineering relating to numerous theories and technologies, which need to be studied continuously by energetic researchers.
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