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Study on damage detection software of beam-like structures

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Abstract. A simply structural damage detection software is developed to identification damage in beams. According to linear fracture mechanics theory, the localized additional flexibility in damage vicinity can be represented by a lumped parameter element. The damaged beam is modeled by wavelet-based elements to gain the first three frequencies precisely. The first three frequencies influencing functions of damage location and depth are approximated by means of surface-fitting techniques to gain damage detection database of forward problem. Then the first three measured natural frequencies are employed as inputs to solve inverse problem and the intersection of the three frequencies contour lines predict the damage location and depth. The DLL (Dynamic Linkable Library) file of damage detection method is coded by C++ and the corresponding interface of software is coded by virtual instrument software LabVIEW. Finally, the software is tested on beams and shafts in engineering. It is shown that the presented software can be used in actual engineering structures.

Keywords: damage detection; wavelet finite element method; LabVIEW; software

1. Introduction

Damage detection in structures is one of the most important procedures for mechanical fault diagnosis in engineering. To avoid the occurrence of outbursting accidents and to prevent overplus or insufficient maintenance of key structures, it is of great importance to implement performance prediction and damage detection (Peng *et al*. 2007). Xiang proposed an wavelet finite element method (Xiang *et al*. 2007a), and then developed a hybrid method by combination of wavelet-based element and neural networks to detect surface cracks in short shafts (Xiang *et al*. 2009). Sinou presented a robust identification of single crack location and size only based on pulsations of the cracked system (Sinou 2007). Currently common used prediction method is model-based method (Montalvão *et al*. 2006). There are two procedures, proposed in the technical literature, to achieve the progress of crack detection in structures (Xiang *et al*. 2008). The first procedure is forward problem analysis, which considers the construction of a stiffness matrix exclusively for the crack section and the computation of crack detection database for natural frequencies or other dynamic

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parameters through the finite element model. Because the crack flexibility is very small, the corresponding coefficient stiffness matrix is extremely large and this might lead to numerical problems during the solution (Saavedra and Cuitino 2001). Lele and Maiti investigated crack identification techniques based on eight-node iso-parametric elements to make more efficient calculation of forward problem for damage detection in beams (Lele and Maiti 2002). Because of crack singularity, both the numerical simulation and experimental studies cannot obtain satisfactory results. In order to control the discretization error, Dutta and Talukdar using an adaptive *h*-version finite element method for bridge damage detection in order to control the discretization error (Dutta and Talukdar 2004). Dong *et al*. presented a parameter identification method of a rotor with an open crack by using the first two natural frequencies and the first mode (Dong *et al*. 2004). Anyhow, most of the published literatures focus on numerical simulation, which are suspect when applied to real structures.

To gain accurate crack detection database of forward problem, the first three influencing functions of damage location and depth are calculated by using high performance wavelet finite element method and the damage detection database are approximated by means of surface-fitting techniques (Xiang *et al*. 2006, 2007b).

The second procedure is inverse problem analysis, which considers the measurement of dynamic parameters and numerical computing or searching for optimization values of crack location and depth from damage detection database (Dong *et al*. 2009, Bukkapatnam and Sadananda 2005, Ikhlas *et al*. 2005, Begambre and Laier 2009).

However, in the open-accessed literatures, fewer researchers developed damage detection software to evaluate damage in structures.

This research is to program a simply structural damage detection software for identification damage in structures, especially for beams and shafts. LabVIEW by National Instrument (NI) is a user friendly and powerful graphical development environment used for signal acquisition, measurement analysis, and data presentation (NI website 2009). By incorporating LabVIEW, the damage detection software by using wavelet finite element method in this research can be obtained easier. A main component of LabVIEW is its ability to simulate a virtual instrument or abbreviated as VI. It involves using specific programming methods and a combination of different measuring hardware to simulate almost any instrument in the computer. A virtual instrument is a system comprising of specially designed software and also a hardware that will convert the input from measuring to digital data to be processed by the computer. The user will employ a computerized test and measurement to collect any data that will be displayed on the computer screen. VIs also could influence systems where the processes are controlled based on data collected and processed by a computerized instrumentation system. VIs could cover anything from specifically written software to log and control processes or even software written to analyze vibration of other signal. A lot of people realized the benefits of VI and hence more and more data collection instruments are designed to work side by side with VIs, creating a field called “virtual instrumentation”. This typically refers to the use of general-purpose computers and workstations with data collection hardware devices and virtual instrumentation software, to construct an integrated instrumentation system. Therefore, many researchers using software LabVIEW to program specially software to achieve their own use in many research fields (Xu and McDaniel 2005, Horng 2008, Corra *et al*. 2009).

The rest of the paper is organized as follows. In Section 2, we introduce basic theory of damage detection method using wavelet finite element method. Section 3 describes how to design software using LabVIEW and C programs. In Section 4, we give some typical engineering applications to testify the performance of the present software.

2. A brief overview of damage detection method using wavelet finite element method

Damage presents a serious threat to proper performance of structures. To detect damages, many model-based methods using finite element method or other numerical method have been rapidly expanding over the last few years. These detection schemes are based on the fact that the presences of damages change the dynamic characteristics of the structures. Fig. 1 shows a beam or shaft with damages on its surface. The geometry of a damage sections in beam and shaft are shown in Fig. 2.

The continuity conditions at damage position indicate that the left node j and right node $j+1$ have the same transverse displacement, namely, $u_j = u_{j+1}$, while their rotations θ_j and θ_{j+1} are connected through the damaged stiffness submatrix $\mathbf{K}_S$ as follows

$$\mathbf{K}_S = \begin{bmatrix} K_t & -K_t \\ -K_t & K_t \end{bmatrix} \tag{1}$$

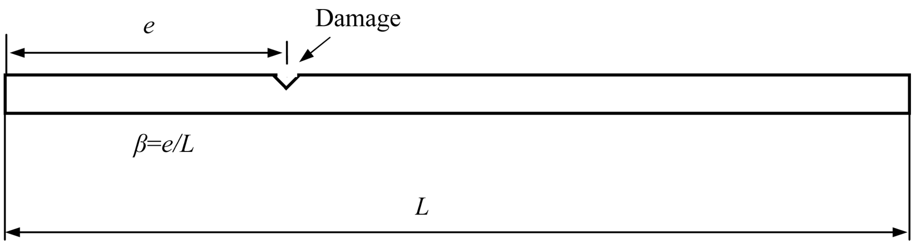

Fig. 1 A beam or shaft with a damage on its surface

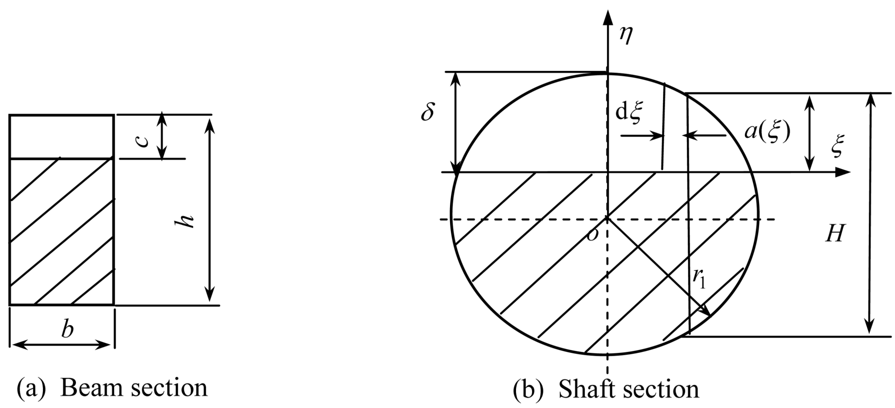

Fig. 2 Geometry of a damage section in beam or shaft

For a damaged beam, K_t is defined by

$$K_t = bh^2E/(72\pi\alpha^2 f(\alpha)) \tag{2}$$

in which

$$f(\alpha) = 0.6384 - 1.035\alpha + 3.7201\alpha^2 - 5.1773\alpha^3 + 7.553\alpha^4 - 7.332\alpha^5 + 2.4909\alpha^6 \tag{3}$$

where $\alpha = c/h$ denotes normalized damage depth as shown in Fig. 1. $\beta = e/L$ in Fig. 2(a) denotes normalized damage location, E is Young's modulus.

For a damaged shaft, K_t is defined by

$$k_t = \frac{\pi E r_1^8}{32(1-\mu)} \frac{1}{\int_{-r_1\sqrt{1-(1-2\alpha^2)}}^{r_1\sqrt{1-(1-2\alpha^2)}} (r_1^2 - \xi^2)[\int_0^{a(\xi)} \eta F^2(\eta/H) d\eta] d\xi} \tag{4}$$

where δ is damage depth, r_1 is radius of the shaft, μ is the Poisson's ratio, $\alpha = \delta/2r_1$ denotes normalized damage depth, $a(\xi) = 2r_1\alpha - (r_1 - \sqrt{r_1^2 - \xi^2})$, $H = 2\sqrt{r_1^2 - \xi^2}$ and the function $F(\eta/H)$ can be given by the experimental formula

$$F(\eta/H) = 1.122 - 1.40(\eta/H) + 7.33(\eta/H)^2 - 13.08(\eta/H)^3 + 1.40(\eta/H)^4 \tag{5}$$

Hence, we can assemble damaged stiffness submatrix $\mathbf{K}_S$ into the global wavelet-based element stiffness matrix. The global mass matrix of damaged structure is equal to the undamaged one. Then, the damaged structural finite element model of wavelet-based elements can be constructed (Xiang *et al*. 2006, 2007b, 2008, Chen *et al*. 2005, Li *et al*. 2005, Nandwana and Maiti 1997) given some specific formulas about wavelet finite element model for beam and shaft by using Daubechies wavelet or B-spline wavelet on the interval (BSWI). The solution of the eigenvalue problem can then proceed as usual. Therefore, the free vibration frequency equations for multi degree of freedoms (MDOFs) system are

$$|\overline{\mathbf{K}} - \omega^2\overline{\mathbf{M}}| = 0 \tag{6}$$

where $\overline{\mathbf{K}}$ and $\overline{\mathbf{M}}$ are the global stiffness and mass matrices.

To gain an accurate damage detection database, wavelet-based element are applied to the forward problem analysis and the first three frequencies influence functions of normalized damage location and depth are approximated by means of surface-fitting techniques. However, in most experimental studies, the difference between measured frequencies and finite element solutions will make the above mentioned method failure. Then, the 'zero-setting' procedure described by Adams *et al*. (1978) is used.

As for the proposed method, the first procedure is forward problem analysis, which considers the construction of a stiffness matrix exclusively for the damage section and the construction of a finite element model of the structures to gain damage detection database. That is the determination of the function relationship between the first three natural frequencies f_j (j = 1, 2, 3) and the normalized damage location β and depth α, as follows

$$f_j = F_j(\alpha, \beta) \quad (j = 1, 2, 3) \tag{7}$$

The second procedure is inverse problem analysis, which considers the measurement of dynamic parameters and the search of normalized damage location and depth, which are given by

$$(\alpha, \beta) = F_j^{-1}(f_j) \quad (j = 1, 2, 3) \tag{8}$$

The procedures for damage detection are given below.

(1) Computing damaged stiffness submatrix $\mathbf{K}_S$ using linear elastic fracture mechanics theory.

(2) Building up the high performance wavelet-based model for damage detection and adding the local damage stiffness matrix $\mathbf{K}_S$ into global stiffness matrix $\overline{\mathbf{K}}$, whereas the global mass matrice remain unchanged.

(3) Continuously computing the first three natural frequencies under different normalized damage location β and depth α.

(4) Using the surface fitting technology to construct a more precision function relationship between the first three natural frequencies and the normalized damage location and depth, i.e., acquire a detection database for forward problem.

(5) Making experimental modal analysis to measure the first three frequencies.

(6) The method of frequencies contour lines plus 'zero-setting' procedure can fulfill the process of inverse problem. In the 'zero-setting' procedure, Young's modulus of the structure is changed by using the undamaged natural frequencies of structures to determine an effective value. namely

$$\left| \omega_i^2 \overline{\mathbf{M}} - E_m \frac{\overline{\mathbf{K}}}{E} \right| = 0 \tag{9}$$

where E_m is the corrected value of Young's modulus E, which can be acquired through solving Eq. (9) for each frequency. This procedure can greatly reduce the error between theoretical analysis and the experimental studies, which are caused by boundary conditions and material parameters.

3. The design of structural damage detection software

The entire damage detection software for beam-like structures is programmed using a LabVIEW program. For researchers who are unfamiliar with the software environment, programming in LabVIEW occurs in two windows. The first window is the Block Diagram where the code development takes place; the other window is the Front Panel where the graphical user interface (GUI) is created. The creation of GUI is similar to the creation of a slide in a PowerPoint presentation; the programmer can select the objects such as controls, devices, plots, or displays from the menu and drop them onto the Front Panel. The position, size, and appearance can be changed using the mouse keys. Before going into the details of the program, it should be mentioned that once the programmer adds a variable or control in one of the windows, the same object is created in the other. However, there exists the possibility to hide the controls or variables in the GUI.

LabVIEW is a programming language with many functional similarities to C, with multiple built-in functions and a graphical programming model that is well suited to creating parallel code. But the ability to reuse code written in other languages as well as being able to be called from external code are also important aspects of programming languages. The Dynamic Link Libraries (DLLs) of core programs are coded by C, such as contour plot program.dll, damaged clamped beam.dll, damaged simply supported beam.dll, damaged shaft.dll and Young's modulus modification.dll, etc. Then the above mentioned Dynamic Link Libraries files are called by LabVIEW-supported platforms to generate damage detection software.

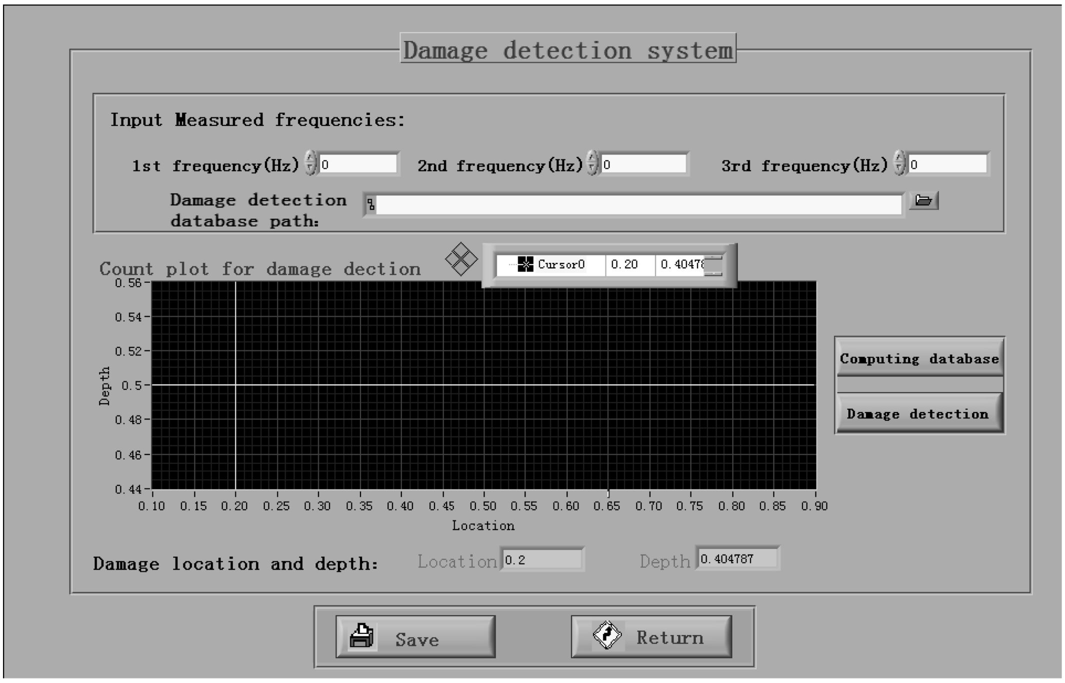

Fig. 3 Main interface of damage detection software

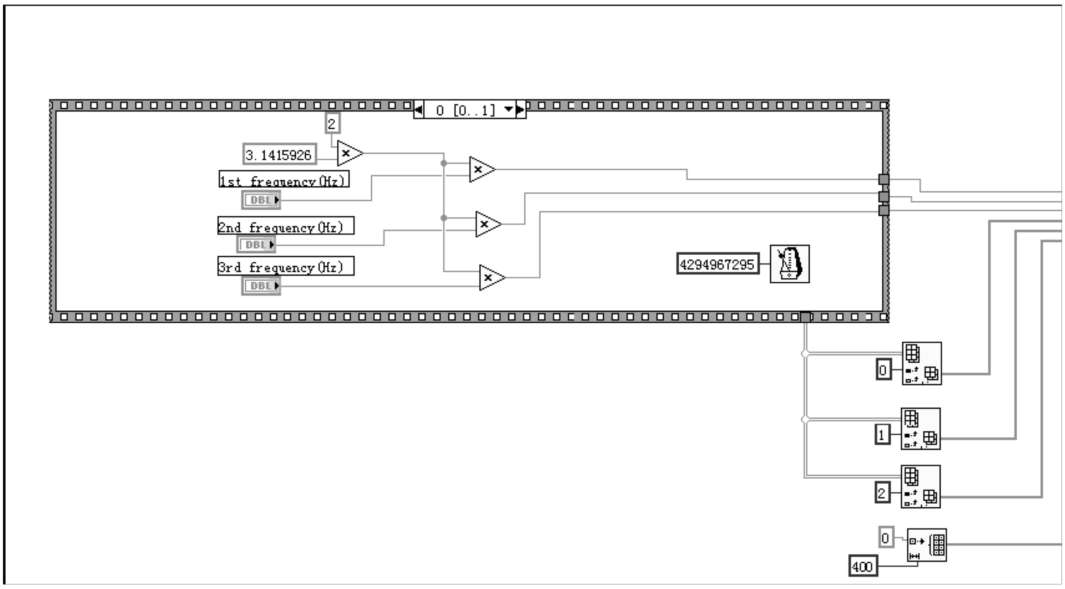

Fig. 4 The G-code flow of the input frequencies

The main interface of damage detection software of beam-like structures is presented in Fig. 3. For the dedicated configuration and has four main parts: input parameters, damage detection process, graphic window and report generation option in the panel. Figs. 4 and 5 show the G-code flow of the input frequencies and damage detection database path input path, respectively.

The input parameters (upper position in the GUI) contains three input windows to input measured frequencies of damage beam-like structures, and one damage detection database file (generated by forward problem analysis of damage detection problem) input path. Three input windows corresponding to the first, second and third measured frequencies, which are tested by using a single

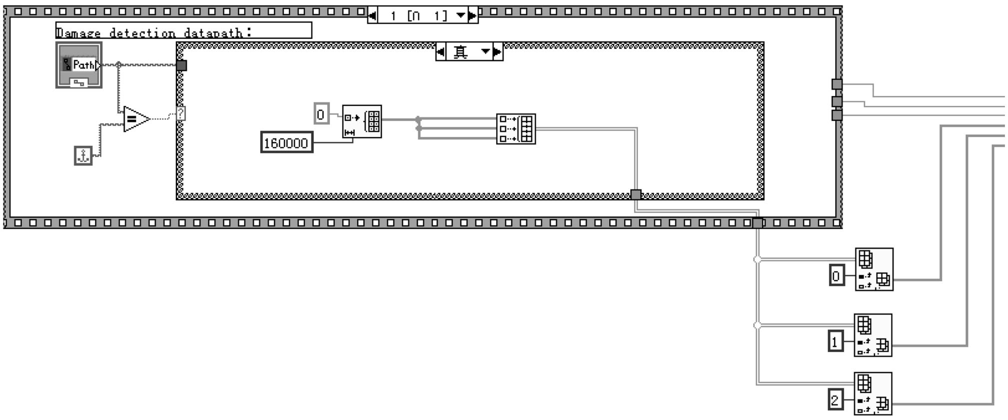

Fig. 5 The G-code flow of the damage detection database path input path

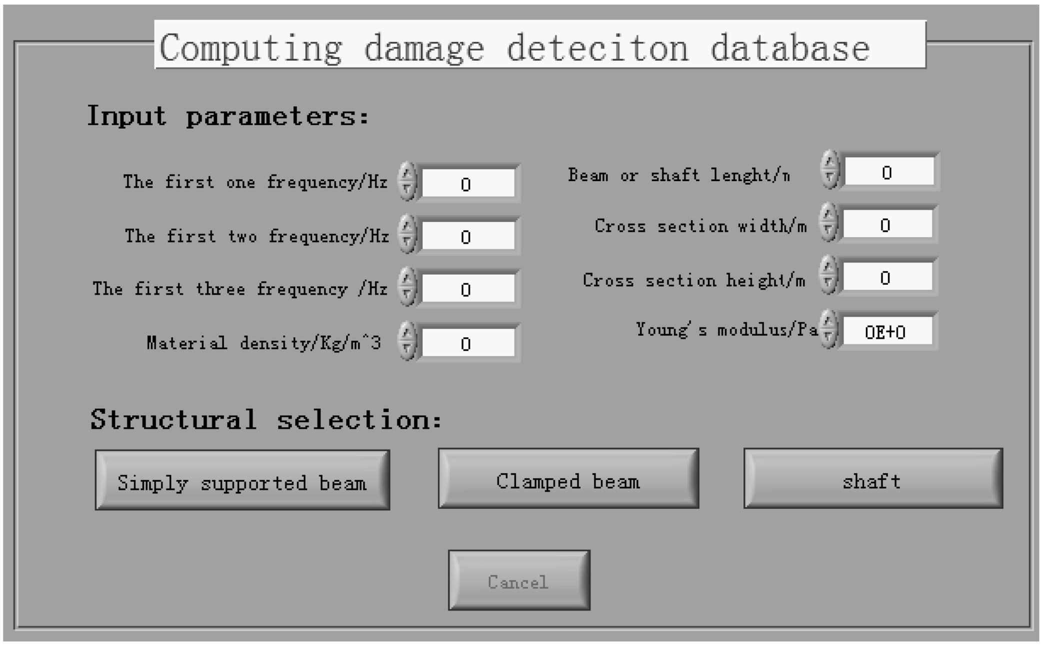

Fig. 6 Computing damage detection database

input and single output (SISO) modal analysis method (Xiang *et al*. 2006).

The damage detection processing options are located in the panel in the right middle corner of the GUI. In this program, some external DLL file, such as damaged clamped beam.dll, damaged simply supported beam.dll, damaged shaft.dll and Young's modulus modification.dll, etc., are used to finish the main body of the presented software. The user can fulfill the forward problem analysis of damaged beam-like structures by clicking the activate button of computing database. Fig. 6 shows the interface of computing damage detection database. The user must (a) set the first one, two and three frequencies in the box labeled, (b) set the material parameters of material density and Young's modulus in the box labeled, (c) beam or shaft length, cross section width and height (for a shaft, the equal diameter are input into the width and height respectively), (d) select the activate button of simply supported beam, clamped beam or shaft to finish the damage detection database computation and saved as a database file. When we input the measured first three frequencies and select the saved database file, by clicking the activate button of damage diction, the inverse problem analysis will be done by seeking the intersection of contour plot and the location and depth of damage structures will be determined.

Because of complex of the program flow, the Block Diagrams have been omitted in this paper.

The graphic window is displayed automatically upon acquisition in a window in the lower left of the GUI. The displayed diagram is gained by calling the contour plot program.dll. The horizontal and vertical cursors are employed as a useful tool to seek the intersection of contour plot so as to digitally display the damage location and depth. Fig. 7 shows a damage detection result for simply supported beam, we can seen clearly that there exist two symmetrical intersections because of the symmetry of structures (Xiang *et al*. 2007b).

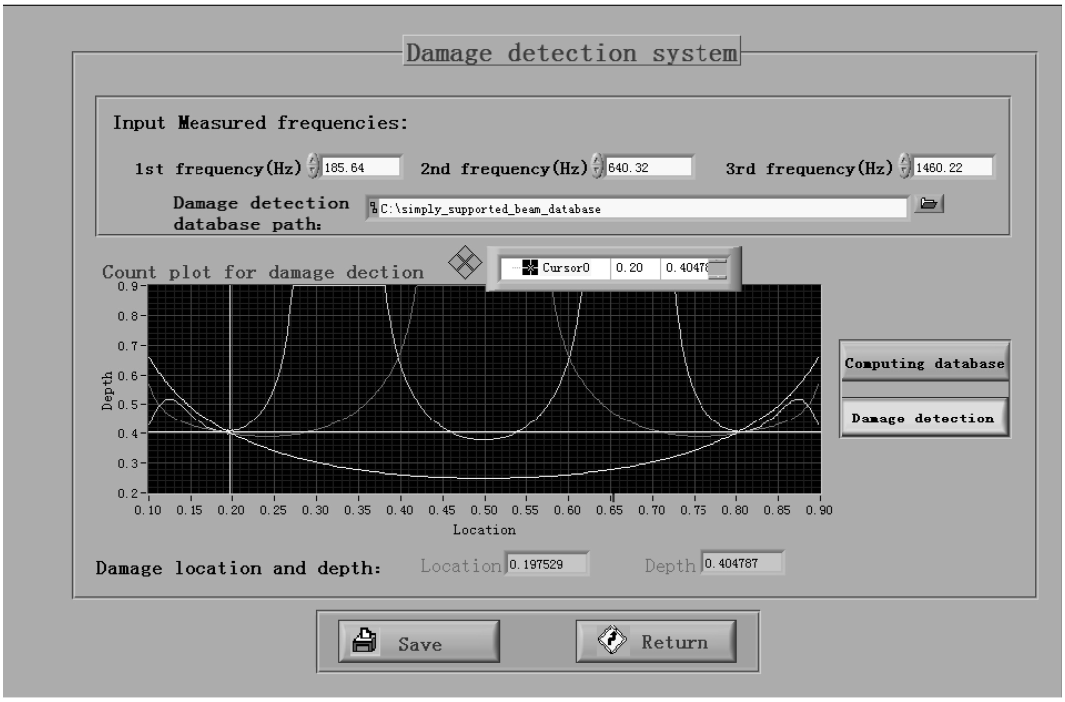

Fig.. 7 Damage detection result for simply supported beam

The report generation option is in the bottom of the GUI. NI LabVIEW Report Generation Toolkit for Microsoft Office V1.1.3 is used to generate report of damage detection results of beam-like structures. A MS word file will be generated automatically by clicking the activate button of Save. If the activate button of Return is clicked, we will quit the damage detection software.

4. Numerical simulation and experimental investigation

***Example* 1**. Taking the cracked cantilever beam for example, beam length L = 0.5 m, Young's modulus $E = 2.1 \times 10^{11}$ N/m^2, $h \times b$ = 0.02 m × 0.012 m, Poisson's ratio μ = 0.3 and ρ = 7860 kg/m^3. The measured first three frequencies of the damage detection software are replaced by the exact first three frequencies (Chen *et al*. 2005, Xiang *et al*. 2008). The Comparison of predicted and actual damage location and depth is shown in Table 1. The predicted damage location and depth have very perfect solving precision. The relative errors are less than 0.4 percent.

***Example* 2**. Changing the boundary conditions of example 1 to simply supported at two terminals. The measured first three frequencies of the damage detection software are replaced by the exact first three frequencies (Chen *et al*. 2005, Xiang *et al*. 2008). Table 2 make a Comparison between predicted and actual damage location and depth. The predicted damage location and depth have very perfect solving precision. The relative errors are less than 0.2 percent.

The good performance of the above mentioned examples demonstrate the accuracy, efficiency and reliability of the present damage detection software for beam-like structures based on wavelet finite element Method, which is developed herein. Because of the damage detection database file can be computed and restored,we can simply input the measured first three frequencies and quickly get the accurate damage information of beam-like structures.

***Example* 3.** Experiment investigation. A laboratory experiment on a test beam structure is conducted to demonstrate and verify the proposed crack detection software.

Table 1 Comparison of predicted and actual crack location and depth for clamped beam

Case	Location	Depth	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	Predicted	Error	Predicted	Error
1	0.1	0.1	66.38	417.65	1171.64	0.1001	0.10	0.1001	0.10
2	0.2	0.1	66.50	418.60	1170.60	0.2004	0.20	0.0999	0.10
3	0.2	0.3	64.24	418.47	1158.99	0.2004	0.20	0.2995	0.17
4	0.3	0.2	65.07	415.55	1136.90	0.3	0	0.2	0
5	0.3	0.3	66.33	413.94	1163.82	0.3	0	0.3	0
6	0.4	0.2	66.33	413.94	1163.82	0.4	0	0.2	0
7	0.4	0.4	64.78	399.47	1139.61	0.4	0	0.4	0
8	0.5	0.2	66.54	411.78	1172.14	0.4984	0.30	0.1998	0.10
9	0.5	0.4	65.68	390.84	1172.09	0.4985	0.30	0.3995	0.13
10	0.6	0.4	66.28	392.31	1132.26	0.6	0	0.4	0
11	0.6	0.6	65.37	356.18	1087.93	0.6	0	0.6	0
12	0.7	0.4	66.61	402.06	1089.16	0.7001	0.014	0.4001	0.025
13	0.7	0.6	66.29	375.87	996.40	0.7001	0.014	0.6002	0.033
14	0.8	0.3	66.78	415.69	1139.81	0.8001	0.013	0.3002	0.067
15	0.8	0.8	66.57	386.44	912.33	0.8003	0.038	0.8013	0.163

Table 2 Comparison of predicted and actual crack location and depth for simply supported beam

Case	Location	Depth	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	Predicted	Error	Predicted	Error
1	0.1	0.1	187.43	748.92	1682.85	0.1001	0.10	0.1001	0.10
2	0.2	0.1	187.23	747.14	1681.14	0.1999	0.05	0.1	0
3	0.2	0.3	185.05	725.40	1636.38	0.1999	0.05	0.3001	0.03
4	0.3	0.2	185.50	739.26	1685.02	0.3001	0.03	0.2	0
5	0.3	0.3	182.93	726.25	1681.99	0.3001	0.03	0.3	0
6	0.4	0.2	184.76	745.89	1678.25	0.4	0	0.2	0
7	0.4	0.4	175.99	733.40	1650.37	0.4	0	0.4	0
8	0.5	0.2	184.48	750.03	1661.01	0.501	0.2	0.2	0
9	0.5	0.4	175.00	750.03	1585.83	0.501	0.2	0.4	0
10	0.6	0.6	159.71	712.96	1605.96	0.6	0	0.6	0
11	0.7	0.4	178.92	707.74	1677.76	0.6999	0.014	0.4001	0.025
12	0.7	0.6	165.93	658.96	1667.00	0.7001	0.014	0.6001	0.017
13	0.8	0.6	175.08	646.21	1515.59	0.8001	0.038	0.6001	0.017

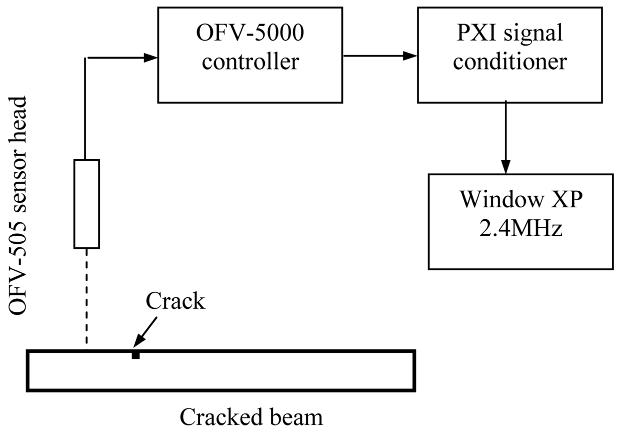

Fig. 8 A schematic overview of the setup

Fig. 8 shows a schematic overview of the setup. The test system consists of a cantilever and simply supported beam with one crack on its surface. A Polytec Doppler laser vibrometer OFV-505/5000 was used to measure the velocities of one point in the beam. We point out here that to measure the first three frequencies only requires one measurement point. The reason is that for the simple structure, single input and single output (SISO) modal analysis by using a hammer as excitation, which is a usually used method. To reduce the reflection of the laser beam and spectral noise, retro-reflective tapes were put on the measurement point in the beam. The laser vibrometer OFV-5000 uses the principle of the heterodyne interferometer to acquire the characteristics of mechanical vibrations. For each cracked beam, the high metrical frequencies can be obtained by using the standard FFT program of the software Matlab.

The length of cantilever and simply supported beams (45# steel) are $L = 0.515$ m and $L = 0.5$ m respectively. The beam cross section is $h \times b$ = 0.02 m × 0.012 m. Material parameters are: Young's modulus $E = 2.06 \times 10^{11}$ N/m^2, Possion's ratio $\mu = 0.3$, material density $\rho = 7917$ kg/m^3. The width of crack width is 0.02 mm, which is made by Wirecut Electrical Discharge Machining (WEDM).

We tested four cracked beams (two cantilever beam and two simply supported beams) each having an open crack at beam with four crack cases as shown in Table 3. The normalized crack sizes α are 0.2 and 0.4 for both cantilever (Cases C1 and C2) and simply supported (Cases S1 and

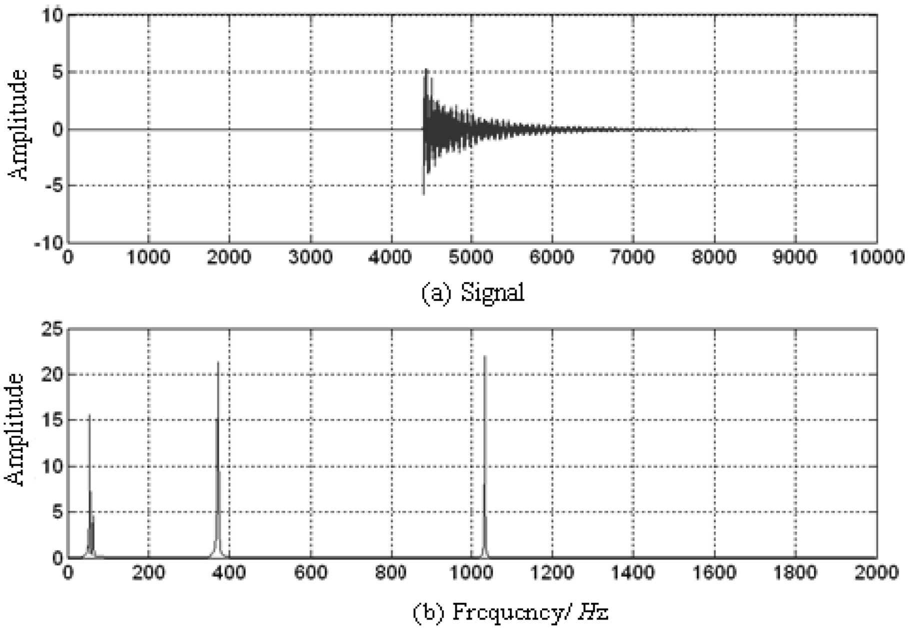

Fig. 9 Impulse signal and frequencies of intact cantilever beam

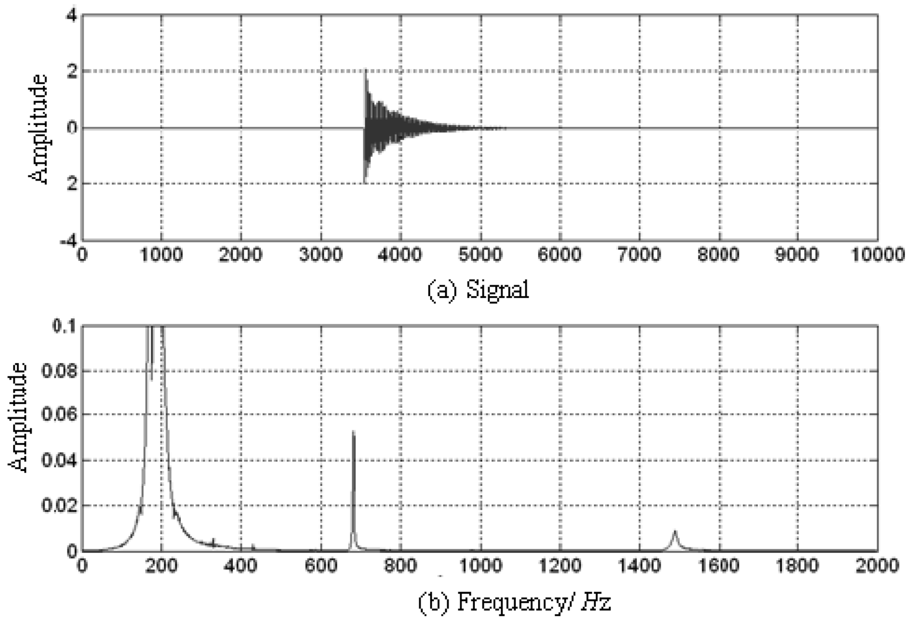

Fig. 10 Impulse signal and frequencies of intact simply supported beam

S2) beams. The normalized crack locations β are both 0.272 for cantilever beam, and 0.2 and 0.4 for simply supported beams. The sampling frequency f_s is 4000 Hz. Figs. 9 and 10 shows the impulse signal and frequencies of intact cantilever and cantilever beams.

The first three metrical frequencies are employed as the inputs of inverse problem for crack quantitative identification. Table 4 shows The metrical and calculated frequencies and the corresponding modified E_m^i. In Table 4, f_1, f_2 and f_3 denote the metrical frequencies, $\hat{f}_1$, $\hat{f}_2$ and $\hat{f}_3$ denote the calculate frequencies. C0 and S0 denote the intact cantilever and simply supported beams respectively.

Fig. 8 shows the crack identification results using the frequency contour plots. The intersection point of three lines indicates the normalized crack location β and size α. In the experimental studies, when the three lines do not meet exactly, the centroid of the three pairs of intersections is taken as the normalized crack location and size. Table 5 shows the comparison of actual normalized crack parameters β and α and the predicted crack parameters β^* and α^*. For the given cases, the relative errors of β^* are not more than 8.8% (Calculated by $|\beta^* - \beta| \times 100$) along beam length while the relative errors of α^* are no less than 9% (Calculated by $|\alpha^* - \alpha| \times 100$). Hence, the

Table 3 The cases for cantilever and simply supported beams

Cases		β	α
Cantilever beam	C1	0.272	0.2
	C2	0.272	0.4
Simply supported beam	S1	0.2	0.2
	S2	0.4	0.4

Table 4 The metrical and calculated frequencies and the corresponding modified E_m^i

Cases		Frequencies and modified E_m^i					
		Calculated frequencies			Metrical frequencies		
		f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	$\hat{f}_1$ (Hz)	$\hat{f}_2$ (Hz)	$\hat{f}_3$ (Hz)
Cantilever beam	C0	54.61	371.54	1034.37	62.1	389.4	1090.1
	C1	54.25	369.05	1030.19	E_m^1 (Pa)	E_m^2 (Pa)	E_m^3 (Pa)
	C2	53.43	369.98	990.49	1.591158e11	1.875321e11	1.853921e11
Simply supported beam	S0	190.4	681.2	1543.6	185	740.2	1665.5
	S1	189.4	674.8	1534.2	E_m^1 (Pa)	E_m^2 (Pa)	E_m^3 (Pa)
	S2	172.8	671.7	1449.3	2.181e11	1.744823e11	1.769728e11

Table 5 Crack detect results

Cases		β^*	Errors (%)	α^*	Errors (%)
Cantilever beam	C1	0.184	8.8	0.290	9.0
	C2	0.304	2.8	0.364	3.6
Simply supported beam	S1	0.238	3.8	0.156	4.4
	S2	0.440	4.0	0.471	7.1

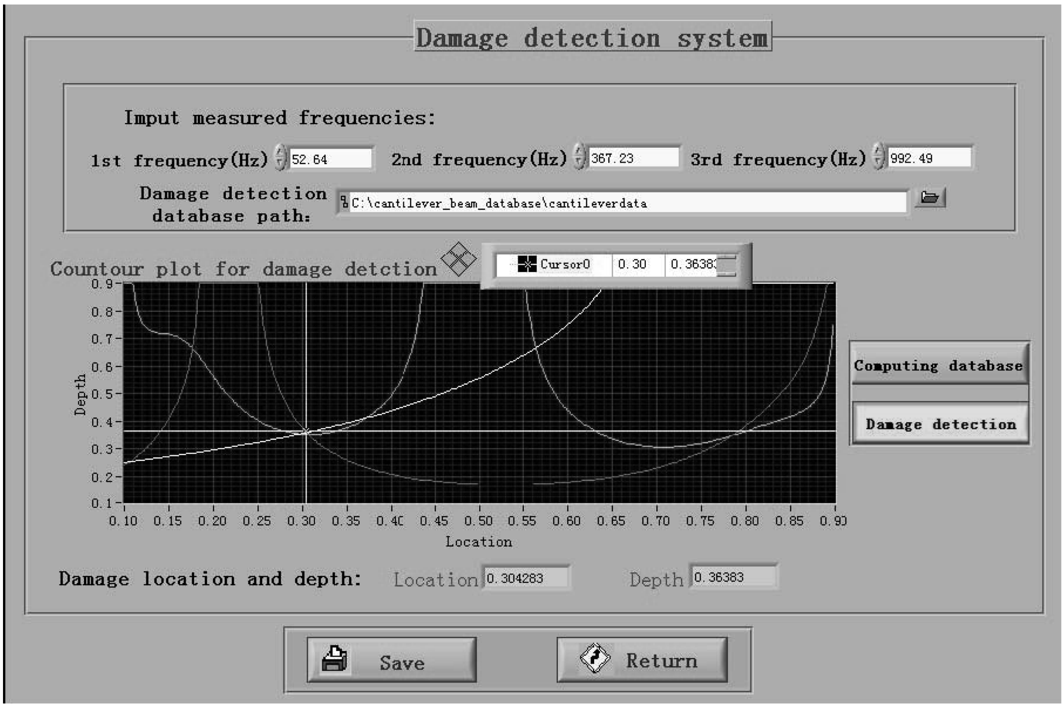

Fig. 11 Damage detection results for Case 2

proposed software is considered to be valid for actual application to detect open cracks in beam like structures.

5. Conclusions

LabVIEW, a commercially integration program environment, can be implemented in the computerization of freshman level structural health monitoring (SHM) software. This decision was motivated by a number of factors which the computing environment should provide the technique worker with an easy way to detect damage in structures, such as beams and shafts. A methodology based on BSWI element to detect damage location and depth is presented. Because the good performance of wavelet-based element, the software presented in this paper is a useful tool to deal with structural damage detection in engineering. The Dynamic Linkable Library file of damage detection method by using wavelet-based element is coded by C and the corresponding interface of software is coded by virtual instrument software LabVIEW. Numerical and experimental investigations verify that the proposed software can be utilized to detect damage location as well as damage depth with high performance.

It is worth to point out that the present software can be extend to stepped beam, the analysis procedures are similar to the simple beam but we have to code an additional Dynamic Linkable Library file for this software. For even more complex structures, we need local modal analysis to obtain the first three natural frequencies so as to solve the inverse problem. Meanwhile, we also need substructure (Suppose it is a simple beam) method to analyze forward problem to obtain the first three frequencies of the substructures.

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