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Design and Experiment of Nondestructive Testing on Broken Wires of Wire Rope

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ABSTRACT

Broken wire is main manifestations of wire rope destruction and timely detection of broken wire can reduce accidents dramatically. A detecting method on broken wires is proposed which is based on principle of leaking magnetic flux of wire rope. Signal data acquisition circuit based on single chip AT89C51 is designed by utilizing integrated Hall element as magneto sensitive element. Damage signal's acquisition, processing and display are completed with LabVIEW software in upper computer and experimental platform is constructed. The experiment results showed that the proposed system can detect the broken wires effectively. The broken position of wires could be located accurately and the error is less than one lay length (70 mm). The system also has the function of differentiating the degree of damage, thus it has popularizing use-value in engineering practice.

Key words: Nondestructive testing, wire rope, leaking magnetic flux, Hall element

INTRODUCTION

As the wire rope has the advantages of high strength, light weight, good elasticity, running smoothly, high reliability, no noise, it could be used in hoist crane, ropeway of freight and passenger transport, elevator, mine hoist. As the loading component in engineering, the wires would be broken due to load in the working process. Its damage condition and carrying capacity are directly relevant to personal safety as well as equipment safety. Safety rules and national examination standards have been made in many countries. However, security incidents caused by wires broken occasionally occur in recent years. In view of this problem, discussions and explorations have been conducted (Henao *et al*., 2011; Zhou, 2002). Li Chunjing carried researches on wire rope tension and virtual simulation which was based on non-contact measurement method (Li *et al*., 2006), but broken wires detecting is not mentioned. Tan (2009) discussed monitoring means and scientific evaluation methods of the wire rope systematically (Tan, 2009). Based on Visio Basic 6.0 software, virtual instrument on damage detecting was constructed and the number of broken wires could be determined precisely but another important damage index, the length of fracture was not discussed. Schmid (2010) proved that vibration testing could be used on rope to find damages (Schmid, 2010). Limited by detecting principle, the wire rope must be tear down from working device to get vibration signal, so the detecting process was cumbersome. Kresak (2012) presented the acoustic and thermo-graphic method in the defect testing of immobile steel wire ropes. The process was only valid for wire ropes in static state. Xiao and Yang (2012) put forward a solution to monitoring the operation quality of the wire-rope-core transmission belt. In this study, leaking magnetic flux of wire rope produced by broken wires is detected, utilizing high performance integrated by Hall elements AH3503 and data acquisition circuit (DAQ) card of damage signal is designed. Damage signals of broken wires are analyzed and processed in VI (Virtual Instrument) system based on LabVIEW software, from which the damage signal could be presented to inspector intuitively.

OVERALL DESIGN SCHEMES OF THE SYSTEM

Wire rope is twisted by steel wire with the feature of high magnetic conductivity and leaking magnetic flux detecting principle is built on character of ferromagnetic materials' high magnetic conductivity. The proposed broken wires detecting system is consist of magnetic actuator, wire rope, magneto sensitive element, DAQ card, virtual instrument of upper computer which is shown in Fig. 1. Wire rope is magnetized to satiation under the exciting of magnetic actuator. When there is no wire broken, most magnetic lines can go through wire rope and the magnetic lines evenly distribute along their axial lines. On the other hand, a part of magnetic lines would leakage out of the wire rope when some of the steel wires are broken. Leaking magnetic signal could be detected by magneto sensor and translated to electrical signal with magnetoelectricity conversion. The received original signal is very weak in addition, disturbances from circumstance factors can't be ignored. Therefore, it needs to be preprocessed and filtered. The whole process can be described as follow: Broken wire signals are sent to single-chip through sampling hold circuit and A/D conversion circuit and the single-chip communicates with upper computer by serial interface according to PC instruction, then in virtual instrument LabVIEW of upper computer, the damage signal is collected and visualized which can be used as judgment reasons by wire rope testers.

MAGNETO-ELECTRIC SIGNAL CONVERSION BASED ON HALL ELEMENT

The working principle of Hall element is shown in Fig. 2a. It can be described as: Control current I is applied in two sides of semiconductor wafer and magnetic filed with magnetic induction U_H which is proportional to the product of I and B will be stimulated in the other two sides of the wafer. Hall potential produced by Hall element is:

$$U_H = K_H IB \tag{1}$$

where, K_H is sensitivity coefficient of Hall element, it's unit is mV/(mA×T).

With the development of electronic and integrated circuit technique, integrated Hall element has appeared which has advantages of high sensitivity, small profile dimension, simple hardware intensity B is imposed in the direction perpendicular to the wafer. Then the electrodynamics force

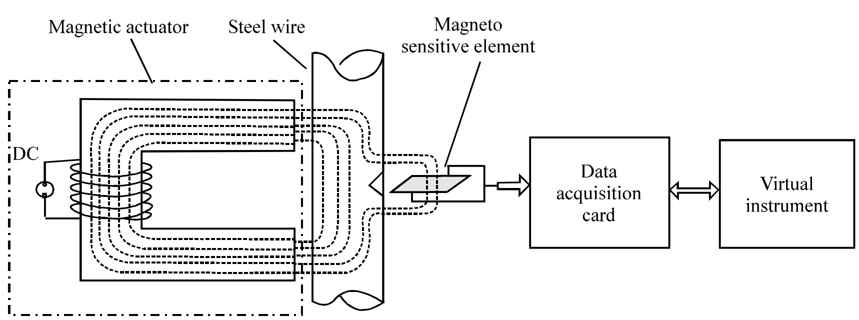

Fig. 1: Diagram of broken wires detecting system

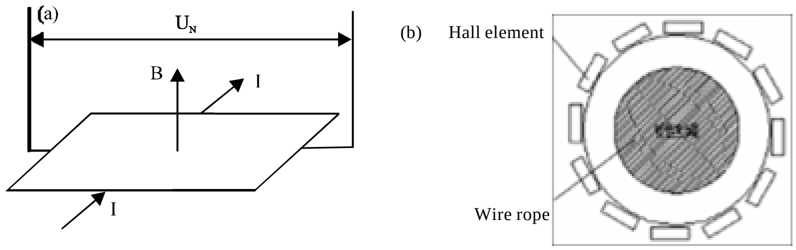

Fig. 2(a-b): (a) Principle and (b) Arrangement pattern of Hall elements

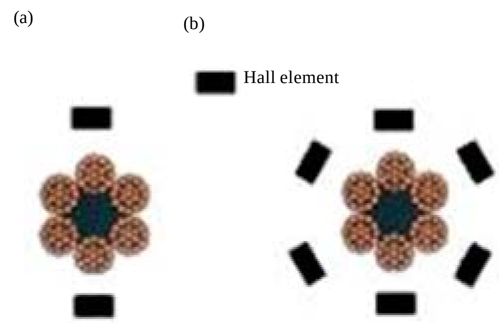

Fig. 3(a-b): Relative position between Hall element and rope strand when the number of Hell element is (a) 2 and (b) 6

circuit and low cost. In this research, AH3503 linear integrate Hall element is used to detect leaking magnitude of wire rope. As single Hall element only catches the damage signal near it, it's difficult to detect damages signal far from it on the same cross section circumference. To deal with the problem, several Hall elements are configured around the wire rope uniformly, forming detecting cycle which is shown in Fig. 2b. In this way, whatever the broken wires appear in anyplace, leaking magnitude due to the broken wires could be detected by Hall element.

Taking 6-strand wire rope as specimen, we discuss the influence of Hall element number apply to test performance. The cross section of wire rope is shown as Fig. 3 and its shape like a hexapetalous flower. As the rope moves along axis, the graph of the cross section is rotating. For a certain Hall element fixed in the detecting circle, when the rope travels the distance of one lay length, circle count of gap between the rope surface and Hall element is exactly same with strand number.

Strand wave signal is caused by kink of rope strands and it is disturbance to useful signals. So, the impact of strand wave signal should be minimized. When the number of Hall elements is 2 and they distribute symmetrically around the detecting circle, rope strand wave signal produced by the 2 Hall elements is in-phase and achieve the minimum or maximum values simultaneously which is shown in Fig. 3a. As a result, interference signal will be double after the selected signal is superposed in adder of DAQ card. In a similar way, when the number of Hall elements is 6, as shown in Fig. 3b, the output of each Hall element varies periodically. The number of Hall element is integral multiple of strand amount and we can see the same result as discussion above. Therefore, the number of Hall elements in this project is set neither divisor nor multiple of strand amount and it should be at 5, 7, 9 and 11. For example, 5 Hall elements are taken to detect

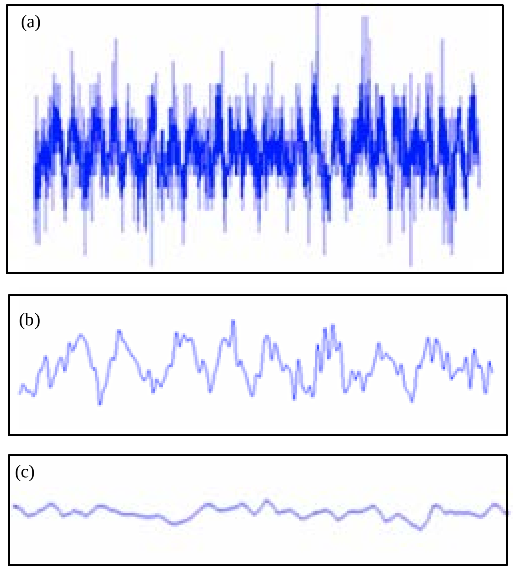

Fig. 4(a-c): Strand waveform produced by different number (a) 1, (b) 3 and (c) 5 of Hall elements

6-strand wire rope and when the cross section rotate 1/30 period, strand wave signal display one period but signal amplitude decreases greatly.

New 6-strand wire rope with no damage is employed as experimental object to validate the above analysis. When the number of Hall element is 1, the detected original data are shown in Fig. 4a, from which we can find that the waveform is not very clear. A clearer waveform could be gotten when the high frequency noises and rags are removed by filtration, as shown in Fig. 4b. Figure 4b reveals that strand waveform takes on a sine distribution which is consistent with the result of analysis. Next, 5 Hall elements are arranged around the wire rope uniformly and the detected strand waveform could be seen in Fig. 4c. By comparison between Fig. 4b and 4c, it verified that the superimposing of several Hall elements could reduce strand wave noise of output signals and the Hall elements number with noise reduction effect is fitted with previous analysis. The proposed design is beneficial to highlight the damage signal and enhance signal-to-noise ratio which has important significance both in theory and practice.

HARDWARE DESIGN OF DAQ FOR DAMAGE SIGNAL

The detector is critical component of providing signal for damage detecting and its performances directly affected accuracy of quantitative judgment, as well as the pattern recognition of damages. Its working process is analog quantity of damage signals trapped in work field are converted to digital values and digital values are transferred to upper computer by serial communication. According to the system function to be completed, the hardware is consist of leaking magnetic flux detecting ring formed by several hall elements, signal preprocesses circuit, anti-aliasing filtering circuit, sample and hold circuit, A/D conversion circuit and communication circuit. The system design flowchart of hardware is shown in Fig. 5.

Signal preprocesses circuit: Two millimeter length fracture of a wire is made in surface of rope. After saturation excitation, Milliteslameter is used to quantify leaking magnetic field. It found that

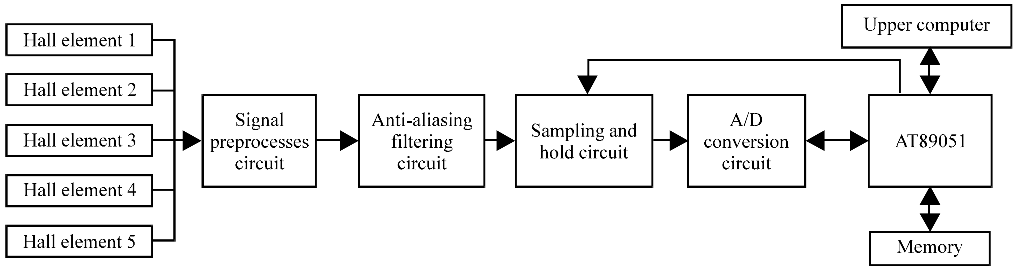

Fig. 5: System design flowcharts of hardware

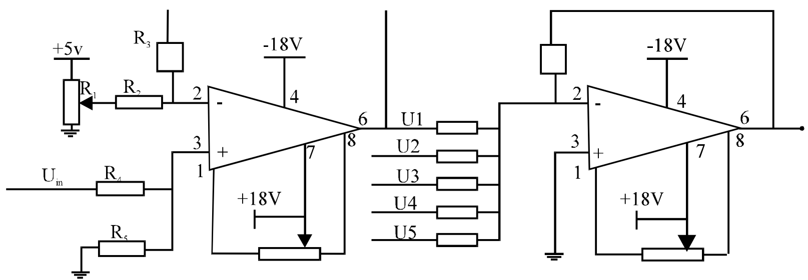

Fig. 6: Signal preprocesses circuit

in distance of 2 mm from rope surface along the radial direction, magnetic flux density is about 6-8 mT. As the sensitivity of AH3503 Hall element is 13.5, so output voltage 80-100 mV of AH3503 can be obtained. However, the output value can't meet the requirement of sampling voltage (0-5 V). Hence, the signal need to be further amplified.

Furthermore, when the input magnetic field is zero, the Hall element output U is about 2.5 V. In order to detect the absolute value, voltage value equal to U is introduced to play the role of differential motion. The designed signal preprocesses circuit is shown in Fig. 6.

The amplifier in the circuit is low power consumption amplifier OP07. It has characteristics of low drift voltage (0.2 μV°C), high precision, good proportional characteristic, low offset voltage at zero point and wider range of applicable voltage (±3˜18V).

Anti-aliasing filtering circuit: In addition to damage signal and strand wave signal, the output of preprocesses circuit also include high frequency oscillation and thermal noise which are produced by detecting elements, amplify circuit and surrounding. This interference broadens frequency band of acquired signals.

Sampling theorem gives the relationship between sample frequency f_s and maximum frequency of band-limited signal f_m:

$$f_s \geq 2f_m \quad (2)$$

Equation 2 shows that only when the sampling frequency f is greater than or equal to the twice of the highest signal frequency, digital signals converted from A/D could be restored to analog signals. Otherwise, reconstructed signals from digital signals will be mixed with aliasing error. In order to meet the requirement of Eq. 2, there are two ways to choose, one is to increase sampling

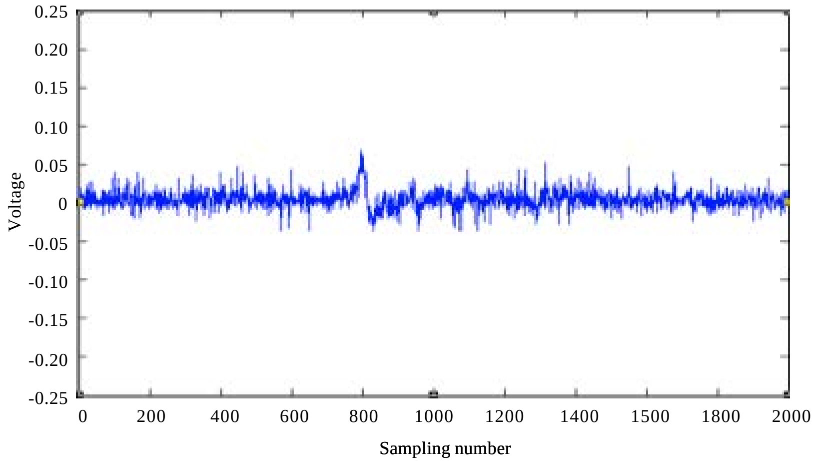

Fig. 7: Original record of broken wire signals

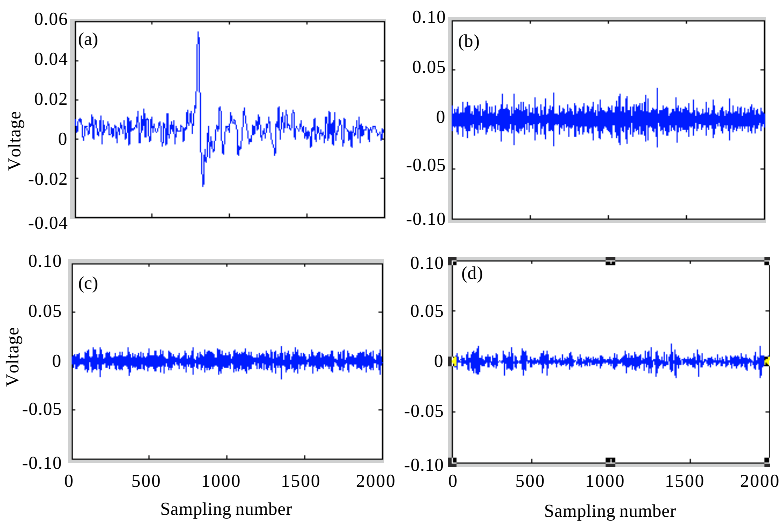

Fig. 8(a-d): Reconstructed signals with wavelet basis DB4 (a) Approximation A3, (b) Detail D1, (c) Detail D2 and (d) Detail D3

frequency f_s, f_s another is to decrease maximum frequency of analog signals. Obviously, the increase of sampling frequency is constrained by objective condition and it has little scope to growth. Hence reducing the maximum frequency of analog signals and filtering out the noise are main research contents in this study.

Based on wavelet decomposition method, frequency-domain analysis and de-noising processing are carried out. DB4 is taken as wavelet basis. Original record signals are shown in Fig. 7. Broken wire signals are decomposed into three layers and the reconstructed signals are shown as Fig. 8. In Fig. 7 and 8, horizontal ordinate is sampling number and vertical coordinates is signal voltage. A3 is reconstructed result of the third layer low frequency coefficient. D1, D2, D3 are reconstructed result of the first, second and third layer high frequency coefficient, respectively.

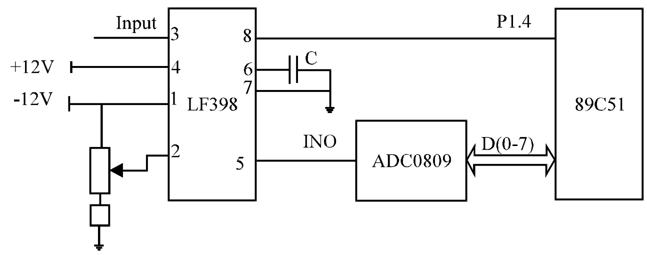

Fig. 9: Hardware connection of sample and hold circuit

Comparison between Fig. 7 with 8 reveals that damage signals is seriously suppressed in detail, so it has no display in D1, D2 and D3. However, damage signals are shown clearly in A3 which illustrates that broken wire signals mostly focuses on low frequency bands.

Sample and hold circuit: The low-cost LF398 of National Semiconductor Corporation is used as integrated sample holder and its hardware connection is shown as Fig. 9.

A/D conversion circuit: After amplified and preprocessed, voltages of damage signals depend upon damage degree and amplification factor of circuit and its values fluctuate in the range of 0-5 V, therefore eight-bit is qualified for accuracy requirement. In the detection process, moving speed of wire rope is less than 30 m min^{-1} which determines the velocity parameter for A/D converter. Taking into account all the above- mentioned elements, we select ADC0809 as the converter for the system.

Communication circuit: There are several modes of communication between single-chip computer and upper-computer, such as serial communication, parallel communication and USB interface communication. Baud rate of serial communication could reach 115 Kbps and valid transmission distance hit 15 m. Transmission rate of parallel port is faster than serial port but its valid transmission distance is shorter than the latter. USB interface has good performance both in transmission rate and valid transmission distance. But it needs firmware programming and the workload is increased. As a result, serial communication mode which is based on RS232 standard, is employed. Single-chip AT89C51 provides a full duplex asynchronous serial communication port, through which the communication between microprocessor and PC may be realized conveniently.

SOFTWARE DESIGN OF DAQ FOR DAMAGE SIGNAL

Damage signal DAQ system is mainly responsible both for accurately measuring of time quantum and uploading the collected damaged data to upper computer. The software is also developed based on hardware circuit of DAQ card. In consideration of the principle of efficiency priority, assembly language is applied in detection software. In main program, a jump instruction is placed in entry.

Firstly, the single-chip is powered and reset and then the main program is loaded and ran. The block diagram of main program is shown in Fig. 10.

The program enters the suspended state after initialization and parameter setting. The upper computer sends the orders of testing or DAQ to single-chip through serial port, therefore the serial port interruption of single-chip is triggered. The results are that, the single-chip respond to interruption and carry out the corresponding interrupt service routine.

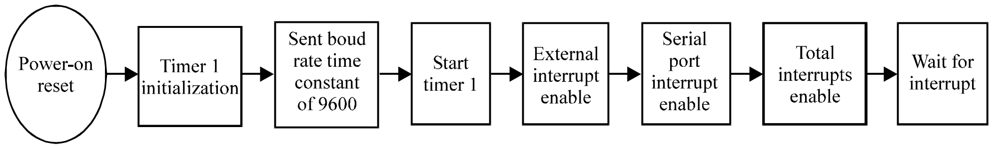

Fig. 10: Block diagram of main program

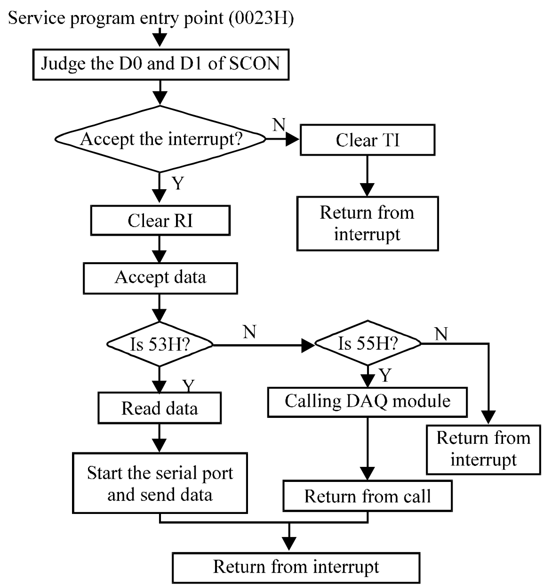

Fig. 11: Serial communication module

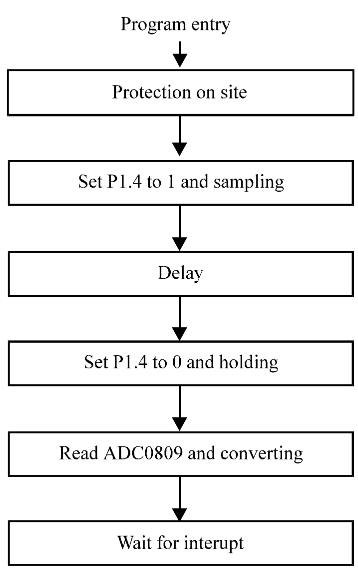

Fig. 12: DAQ module

In this project, interrupt service routine mainly include the serial communication module and DAQ module and the block diagrams are shown in Fig. 11 and 12, respectively.

VIRTUAL INSTRUMENT SYSTEM BASED ON LABVIEW

Computer recourses and instrument hardware are deeply integrated in LabVIEW platform. The hardware of the traditional instruments is replaced with powerful software of current computer and friendly user-computer interaction is realized. Therefore, the design reduces the size and cost of the hardware.

The DAQ card which takes single-chip microcomputer AT89C51 as core and use MAX232 to shift electrical level, transfers data with LabVIEW analysis system of PC through serial port, thus realize the functions of damage signal's acquisition, processing, analysis, display, storage, playback, etc. The connection relationship between VI system and slave computer is shown in Fig. 13.

The Virtual Instrument (VI) system includes master processor module, DAQ module and data disposing and analysis module. The master processor which dominate all the other modules is the top floor of the software and it execute the tasks of control, calling program, organization, coordination between the functional modules and then complete the control of signal testing and analysis. DAQ module is responsible for trigger control of signal processing system, serial device driver to PC and data management. Primary mission of data disposing and analysis module is signal filtering, playback, time-domain analysis and wave display. Software block diagram of virtual instrument system is shown in Fig. 14.

EXPERIMENTS

Experimental system configuration: The experiment equipments include notebook computer, DAQ card of damage signal card, steel wire (1.5 m of length), electromotor and magnetic actuator, as shown in Fig. 15. Stimulated by direct current, magnetic actuator produces magnetic field which magnetize the wire rope to saturation state. Wire rope is dragged by electromotor, passing through pole shoe and signal's DAQ card. If the wire rope has broken wire at some point, the magnetic flow would leak out from the surface of the wire rope. When the damage point goes through the DAQ card, leakage flux will be snapped by Hall element and converted to electrical signal. Upper computer sends signal acquisition instructions to serial port and read the damage signal from serial port, therefore the damage signal would be displayed in LabVIEW platform.

Experimental procedures and results analysis

- A test-piece of wire rope is taken, with a wire fracture of 2 mm length made at 550 mm to the left end and another wire fracture of 1 mm length made at 1200 mm to the left end which is shown in Fig. 12a
- DAQ card with its nine-pin serial port plugged into a laptop is then fixed on the exciter and apply power
- Open the Labview main program and send the command to slave machine, requiring it to acquire data. Meanwhile star the motor and run it at the speed of 30 m min^{-1} (500 mm sec^{-1})

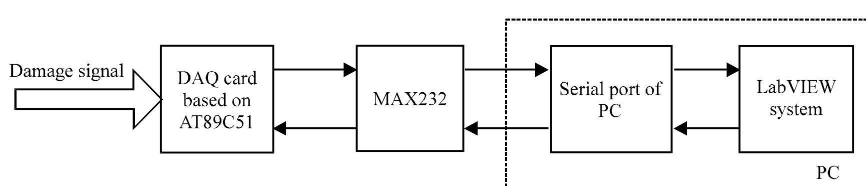

Fig. 13: Connection relationship of LabVIEW and DAQ card

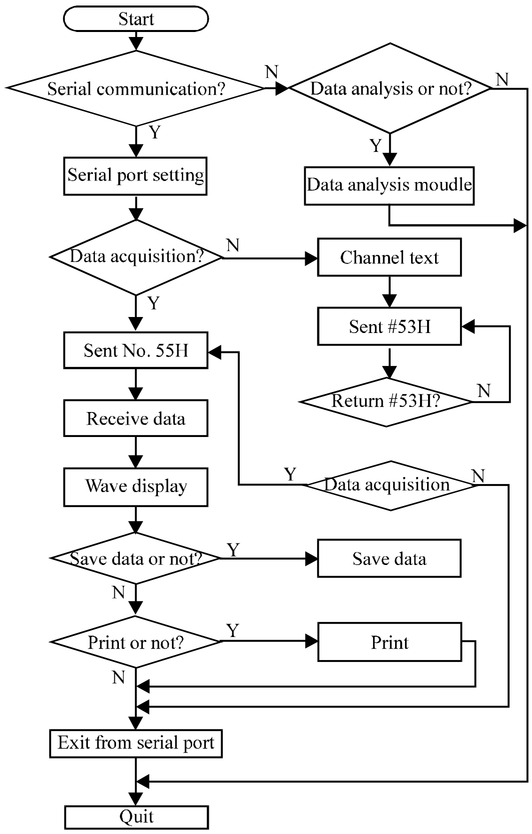

Fig. 14: Program chart of Virtual Instrument (VI)

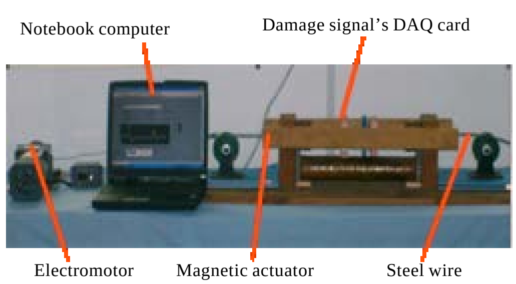

Fig. 15: Experimental instrument of broken wires detecting

which will drag the steel rope to move inside the magnetic excitation machine and DAQ card. When the end of the rope reaches the card, turn off the motor and send the stop command to the slave machine

- Enter the LabVIEW data analysis module. Figure 12b shows the results of the 3rd order Bessel function based digital filter results whose stop frequency is 20 Hz. The results directly indicate the strength and the location of the broken wire. The first broken location is at point 389 and the second one is at point 1468
- Analysis of experimental results. The location of the broken wires can be calculated from data shown in Fig. 12b

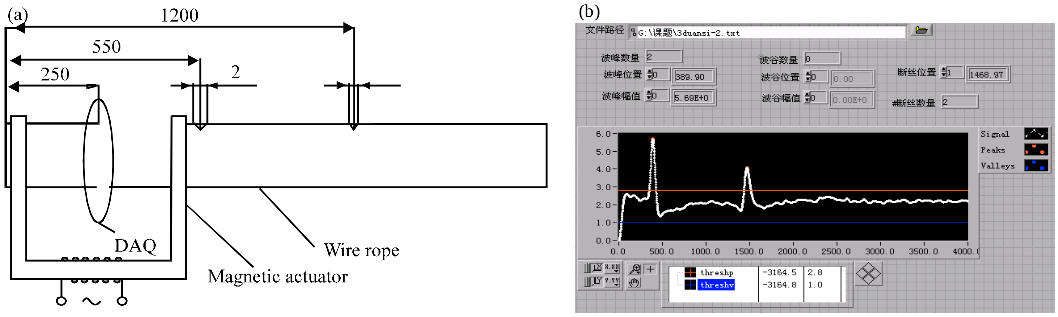

Fig. 16(a-b): (a) Broken wires location and (b) Experiment result

$$l_1 = 250 + \frac{v}{f_s} \times 398 = 250 + \frac{50}{800} \times 398 = 490\text{mm} \tag{3}$$

$$l_2 = 250 + \frac{v}{f_s} \times 1468 = 250 + \frac{50}{800} \times 1468 = 1160\text{mm} \tag{4}$$

where, l_1 the distance of the first broken wire to left end of the wire rope specimen, v traveling speed of the wire rope, l_2 the distance of the second broken wire to left end of the wire rope specimen, f_s sampling frequency of DAQ, its value is determined by slave machine program and in this research f_s is set to 800 Hz.

Comparing, l_1, l_2 with the location of two broken wire, respectively, it found that the errors are within one lay length of specimen (70 mm). In addition, signal strength of broken wire located in 550 mm is significantly larger than the location of 1200 mm which indicate that the larger the length of fracture, the stronger the damage signal is. The location of broken wires and experimental results shown in Fig. 16.

CONCLUSION

Broken wire is one of main manifestations of wire rope destruction. Furthermore, other form destructions would be revealed in the form of wire broken eventually. Consequently, it's key to get the broken wire information from nondestructive testing on wire rope. If there is broken wire in wire rope which is excited to saturation, magnetic line of force would be leaking out to the air. With that mechanism a nondestructive testing method on broken wires is proposed:

- Hall elements are evenly distributed around the wire rope which constitute detector ring. The project avoids missing detection and eliminates strand wave effectively
- Broken wire detecting system which is based on LabVIEW has the advantages of simple programming and high reliability. And the damage signal can be displayed more dearly and directly
- Compared to existing methods, the system could realize quantitative determination on different fracture length of wires

- The experimental results indicate that the system could detect broken wire accurately and could locate the position of the broken wire. The detection error is less than one lay length (70 mm). What is more, the level of damage could be discriminated successfully

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