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Development of Nondestructive Detecting System for Elevator Wire Ropes using Hall-effect Sensors

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Hall 센서를 이용한 엘리베이터 와이어 로프의 비파괴 검출시스템의 개발

김 성 덕

Abstract

Wire ropes have been widely used in industrial applications, wherever heavy weight should be carried safely or mechanical energy should be transmitted fast. Especially, wire rope failures in operating elevator may lead to extensive property damage and serious injury to nearby personnel. Hence, it is very important to inspect wire rope periodically. Failure detection of wire rope requires fundamental knowledge of wire rope construction, rope behavior, properties of fault, sensing and signal processing method. In this research, the development of a new fault detecting system incorporating Hall-effect sensors to detect flaws such as abrasion, broken wire, corrosion and deformation for aged wire ropes in elevator, is described. For using a detector as a portable instrument, several performances for implementing sensing part with Hall-effect sensor, analog signal processing unit and programs are described. Experiments and field testing results for the implemented detecting system are also given. As a result, it is verified that the detecting system has good efficiency for inspecting faults of aged wire ropes in service.

요 약

와이어 로프는 무거운 중량을 안전하게 운반하거나 기계적인 에너지를 빠르게 전송하는 곳과 같은 산업응용 분야에 광범위하게 사용되어 왔다. 특히, 운전 중 엘리베이터의 와이어 로프가 파손되면 큰 재산 상 손실과 주변 인명의 심각한 상해를 초래할 수 있다. 따라서, 와이어 로프의 정기적인 검사는 매우 중요하다. 와이어 로프의 고장 검출은 로프의 구조, 특성, 결함 특성, 검출방법과 신호처리 방법에 대한 기본적인 이해가 요구된다. 이 연구에서는 엘리베이터에 노화된 와이어 로프에 대한 마모, 단선, 부식과 형붕괴와 같은 결함을 검출하기 위하여, Hall 센서를 결합한 새로운 결함 검출시스템의 개발에 대하여 다룬다. 휴대용 계측기로서 검출기를 사용하기 위하여, Hall 센서를 가진 센싱 부분과 아날로그 신호처리 및 프로그램의 제작에 대한 몇가지 특성들이 서술되었다. 제작된 검출시스템에 대한 실험과 실장시험 결과 역시 제시되었다. 그 결과, 검출시스템은 사용 중인 노화된 와이어 로프의 결함을 검출하는데 양호한 효율성을 갖는다는 것을 확인하였다.

1. Introduction

One of the most economical components, wire rope is used in a myriad of various industrial applications such as elevator, mine hoist, construction machinery, crane, lift and suspension bridge. Especially, elevator usually uses in many persons so that its safety is very important. Elevator is a precision-made and complex machine composed of more than 20

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thousand parts. It can cause casualties and damages if it fails to operate properly[1,2]. As wire rope usually takes charge of total weight of elevator and then, to hold safety of elevator, it is necessary to periodically inspect flaws or deterioration in operating wire ropes. Hence, the maintenance and replacement of wire ropes should be determined based on precise measurement data of wire rope in service.

The principal deterioration modes of steel wire rope can be categorized as loss of metallic cross sectional area and localized faults[3]. In general, the metallic cross sectional area of wire rope is reduced due to external or internal abrasion or corrosion. Most loss of cross sectional area is caused by external abrasion such as rubbing along floors or other surfaces. Of course, internal corrosion caused by environmental condition is important because it can not be detected by visual inspection. Localized faults such as broken wires, kinks or other mechanical damages would occur by fatigue or wear in the wire rope and it is also important to hold safety of operating wire ropes. According to inspection regulation of Korea Elevator Safety Institute[4], elevators should be inspected in accordance with the specifications.

Although many NDT procedures such as optical, acoustical and mechanical methods have been tried to inspection wire rope faults, only visual inspection and magnetic test methods are available in practice. The most obvious and the simplest method of testing a rope for flaws is by visual inspection, but it can be detected by only surface flaws and take much labor in inspecting wire rope. Furthermore, it could not detect any internal defect in the aged wire rope and its inspection results may be unrealizable to give degree of deterioration of wire rope.

Electromagnetic wire rope inspection instruments have been developed over the past several decades[5,6]. Electromagnetic methods for testing of aged wire ropes in service are more reliable than purely visual inspection. Such methods would provide great insight into the condition of a rope, despite of less careful test procedure. Moreover, they would give any inform of external and internal defects and it would also provide reliable and sensitive results. And a permanent record for the wire rope conditions is readily available. Although many trials have been in developing wire rope testers, there are still some troubles such as uneasy carrying weight, assessing the results or keeping very sensitivity to inspect elevator wire ropes. Hence, it is required to develop a suitable and potable instrument for elevator wire ropes.

2. Faults in Wire Ropes

2.1 Fault and Its Inspection

There are many kinds of wire ropes used in industrial equipment but 2~3 types of wire ropes are often used in elevator. The principal deterioration modes of steel wire rope can be categorized as loss of metallic cross sectional area and localized faults. In general, the metallic cross sectional area of wire rope is reduced due to external or internal abrasion or corrosion. Most loss of cross sectional area is caused by external abrasion such as rubbing along floors or other surfaces. Of course, internal corrosion caused by environmental condition is important because it can not be detected by visual inspection. Localized faults such as broken wires, kinks or other mechanical damages would occur by fatigue or wear in the wire rope and it is also important to hold safety of operating wire ropes.

Almost without exception, failure of wire rope poses an extremely serious safety hazard and then, it is necessary for operating wire ropes to inspect periodically to keep safety. In domestic area, it is recommended that the inspection of elevator wire rope should be undertaken regularly at interval of every one year regarding to the Regulations for the Industrial Safety and Health Act[7].

In general, wire rope is usually tested by only visual inspection in domestic area, regarding to inspection criteria specified by the relation Regulation. This test method is simple, convenient and inexpensive but its inspection result is always unreliable and further, such method never detects internal corrosion.

Although many NDT procedures such as optical, acoustical and mechanical methods have been tried to inspection wire rope faults, only visual inspection and magnetic test methods are available in practice. Electromagnetic wire rope inspection instruments have been developed over the past several decades[1~3, 5,6]. Electromagnetic methods for testing of aged wire ropes in service are more reliable than purely visual inspection. Such methods would provide great insight into the condition of a rope, despite of less careful test procedure. Moreover, they would give any inform of external and internal defects and it would also provide reliable and sensitive results. And a permanent record for the wire rope conditions is readily available. Although many trials have been in developing wire rope testers, there are still some troubles such as uneasy carrying weight, assessing the results or keeping very sensitivity to inspect elevator wire ropes.

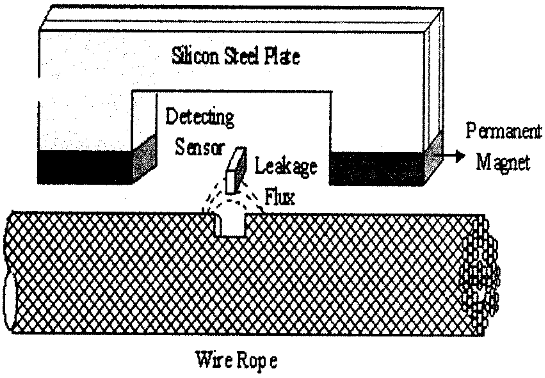


Figure 2.1 Hall sensor and magnetic head

A rope to be inspected should be magnetically saturated a priori and then, the axial magnetic flux in the rope is proportional to its cross sectional area. Although loss of cross sectional area of wire rope due to deterioration could be measured by sensor located on the path of the main magnetic flux, it is general to detect magnetic leakage flux caused by flaw in the wire rope, as shown in Figure 2.1. Therefore, it may be required to use any magnetic exciting unit with high intensity of magnetic flux in order to hold saturated rope and to select a suitable sensor having good sensitivity. Most of electromagnetic test instruments would use a DC exciting coil, which has stable performance and strong magnetic intensity. However, it has always a heavy weight due to a magnetic generating device so that such exciting device could not use in inspecting wire ropes installed in an elevator or lifter. In resent years, there has been developed any bonded type of permanent magnets having very high intensity and then, more light weight magnetic supplier could be used in portable magnetic device such as rope tester.

2.2 Hall-effect Sensor

Various types of sensors have been applied to measure the major magnetic flux in the magnetic head and the magnetic leakage flux around the wire rope, but leakage flux sensor would provide better sensitivity and quantitative resolution. For the purpose of this, there are usually 2 types of detecting sensors, which are inductive sensor and Hall-effect sensor. In general, output of inductive sensor is determined, dependent upon detecting speed and it can be easily affected by environmental magnetic flux. Hall-effect sensor[8] can gives a velocity-independent signal while its output may be very small. However, its minute output could be amplified by using high gain amplifier and it has good sensitivity.

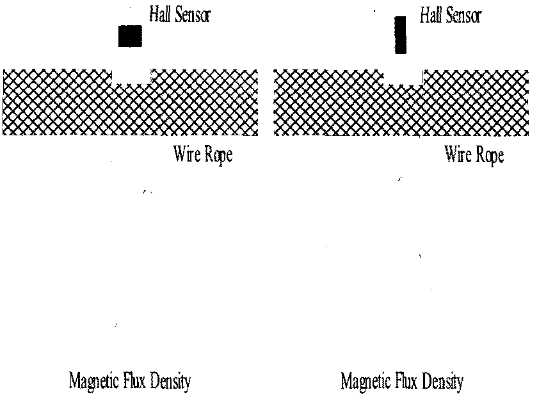
Hall-effect sensor provides its output signal independent of inspection speed and further can detect the presence and size of such defects as abrasion, corrosion, broken wires and deformation. Hall sensor can measure either the major magnetic flux or the magnetic leakage flux, depending on the location. Although both measurement methods could be applied to develop any NDT instrument of wire ropes, the magnetic leakage flux sensing technique usually uses due to high sensitivity and good resolution.

In general, both components in the magnetic leakage flux are strongly affected by various parameters of the flaws in the wire ropes such as sensor size, probe location and defects. Hence, sensor system should be designed to accomplish some requirements, such as short distance measurement, high sensitivity and quantitative results for all types of flaws. In general linear Hall sensors, the output voltage V_h of the Hall plate is given as

$$V_h = k_h IB\sin\theta \tag{1}$$

where $k_h = R_h/d_h$ denotes the sensitivity of the Hall sensor. R_h and d_h are the Hall coefficient and the thickness of the Hall plate, respectively. Further, I is the current passing through the Hall plate and B is the vector of the magnetic flux density perpendicular to the surface of the Hall plate. And θ denotes the angular between the Hall plate and the magnetic flux. If the current I is constant, the magnetic flux density B is proportional to the sensor output V_h.

The magnetic leakage flux around the wire rope shows different output depending upon the direction of Hall sensor plate. The radial component B_r of the magnetic leakage flux density can be measured as the Hall plate is located to be parallel to the axis of the wire rope, shown in Figure 2.2(a). However, the tangential component B_t can be detected for the Hall plate to position perpendicular to the axis of the rope shown in Figure 2.2(b). Although 2 types of Hall sensor direction when inspecting fault of wire rope, it would be better that Hall sensor is located to vertical direction to the leakage flux because of showing good sensitivity and assessing fault types. Hence, the structure as shown in Figure 2.2(b) is applied to design a wire rope detector.



(a) horizontal direction (b) vertical direction

Figure 2.2 Output for linear hall-effect sensor

In general, detecting sensitivity is determined by magnetic saturation, sensitivity of Hall sensor and further, locating distance of magnetic poles. The properties as shown in Figure 2.3 appears only when the length of the fault is usually less small than that of magnetic poles. If not, the Hall sensor response gives an averaging value according to the distance of poles[9].

3. Detector System Design

3.1 Schematic Design

Outputs of Hall sensors could be displayed on the CRT in a PC(or notebook) through any analog and digital signal processing in other that inspector can be easily known defects of wire rope from the results with on or off-line. Figure 3.1 demonstrates an overall schematic diagram for fault detecting system of wire rope.

Detector system consists of a sensing unit, analog signal processing unit, master microprocessor, a mini printer and 7-segment display. And the designed detector system is interfaced to a PC, which has capabilities such as control the electronic unit and measure sensor output in real time. Outputs of Hall sensors are converted or amplified to suitable levels in the analog signal process and then, they are converted to digital data in A/D converter. Main microprocessor controls all the other microprocessors, which are including in A/D converter, display units or printer controller.

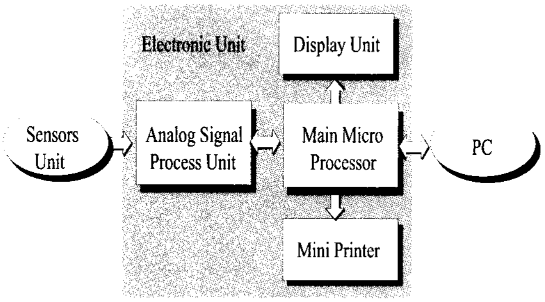


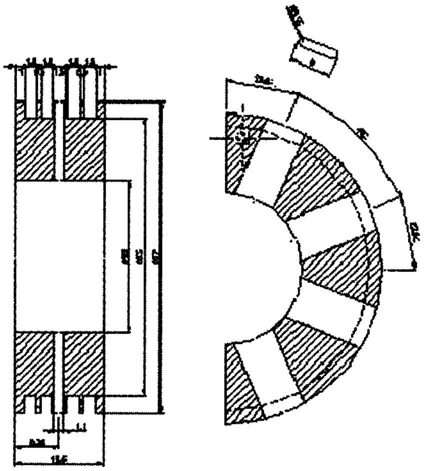
Figure 3.1 Overall schematic diagram for detector

3.2 Sensor and Sensing Head

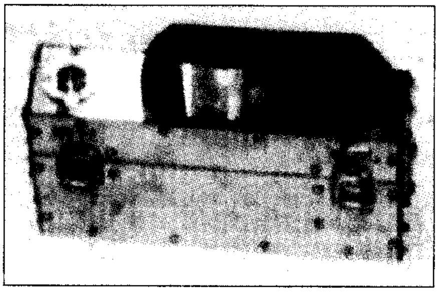
As mentioned above, fault detector for aged wire ropes consists of a magnetizing unit and a signal detect unit. To detect deterioration around aged wire ropes, it is required that the test wire rope should be magnetically saturated and the magnetic leakage flux would be generated sufficiently to enable to detect by the Hall sensor. Although any encircling coil excited by high DC current is available in order to saturate the steel wire ropes, it may be common that developed instruments with an encircling excitation coil is too heavy to use it in inspecting elevator wire ropes in situ. Fortunately, bonded type permanent magnets instead of DC magnetizing coil can be used, which has strong magnetic intensity and small size. Therefore, we use 8 Nd-Fe-B permanent magnets and 8 Hall sensors as shown in Figure 3.2.

In practice, the sensing head with circular Hall sensor structure could be clipped around strung wire ropes to be able to detect leakage flux along the wire ropes, it has to be split into two parts. To increase measurement sensitivity, the Hall sensor should be closer to the surface of wire rope as possible. Figure 3.2(b) shows an implemented sensing head having 2 hinges.

On the other hand, to implement a sensing head with light weight and small size, the distance between each magnetic poles is 97.6[mm] is designed and the Hall sensor having 1[mm] width is located at the center of such sensing head. Sensor output is dependent of the distance of magnetic poles and the size of fault for the designed detector[9] but detailed analysis for such performances is omitted here.



(a) sensing head



(b) implemented sensing head

Figure 3.2 Mechanical configuration

3.3 Signal Processing Unit and Program

In general, variation of Hall sensor output caused by faults should show any suitable data in order that the inspector could be known fault types or their quantitative levels through measurement data. Therefore, electronic unit in the fault detector comprises analog signal processing unit, A/D converter, display, printer controller and microprocessor unit.

In typically, some of commercial linear Hall-effect sensors have their own driver/controller, but it is designed to supply a constant voltage regulator for Hall sensors in this research. Output voltage of a Hall sensor is very small in detecting the response of minute magnetic leakage flux due to small faults. Hence, each output of 8 sensors is summed and amplified to a suitable level. To measure all defects around the wire rope, 8 Hall sensors are used to a circular form. In analog signal processing unit, output of each Hall sensor is summed and amplified to a suitable measurement level. Further, there may exist any offset voltage in the output of Hall sensor so that an off-set circuit is designed in this unit.

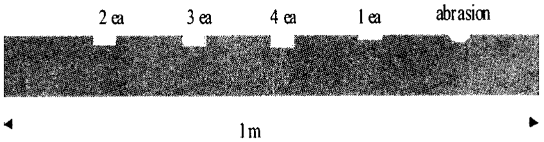
Output of analog signal process is converted into corresponding digital data by using 16[bit] A/D converter. A micro controller in this A/D converter unit controls A/D converter operations such as start/end command, sampling interval, averaging data or conversion, and further, it drives 7-segment display. Master microprocessor receives conversion data from A/D converter and analyzes these data. Moreover, it is interfaced to external devices such as 7-segment displays, mini printer and PC. These devices are designed micro controllers to perform suitable operations.

In implemented detector system, 2 types of programs are designed. One is to operate electronic unit, which control the detecting system hardware and measure faults of wire rope. The other is to measure, analyze and display data in a PC, i.e., measurement program. This program has capabilities such as assignment of communication port, changing of transmission speed, choosing of data number, sampling interval or so.

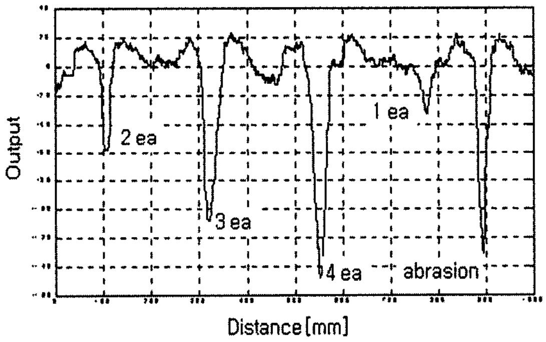
4. Basic Experiment and Field Test

4.1 Basic Experiments

To examine some performances for the implemented detector system, a sealed type wire rope, 8S(19) for elevator is prepared, which consist of 8 strands and 152 steel wires. To verify the detecting property, an artificial wire rope was testing. In practice elevator, the normal speed of wire rope is over 15[m/min] but it can be adjusted to 5[m] when inspecting it. To verify detecting property of the developed system in detail, the rope speed under testing in the laboratory is much less slow than that of practical elevator by using a stepping motor driver. The speed of wire rope is set to 0.3[m/min] and the sampling interval is given to 100[ms].



(a) shapes of faults



(b) testing result

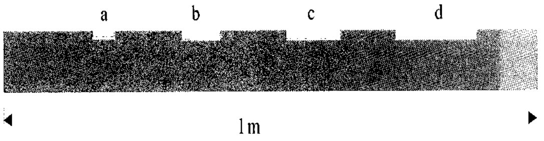
Figure 4.1 testing wire rope with artificial faults

First, the prepared wire rope has several broken parts on the surface of wire rope strands in the outer layer. As shown in Figure 4.1(a), rope length is approximately 1[m] and length of broken wire is 5[mm] but the last part is an abrasion flaw. If the number of broken wires is 4, the loss of cross sectional area becomes to be approximately 2.6[%].

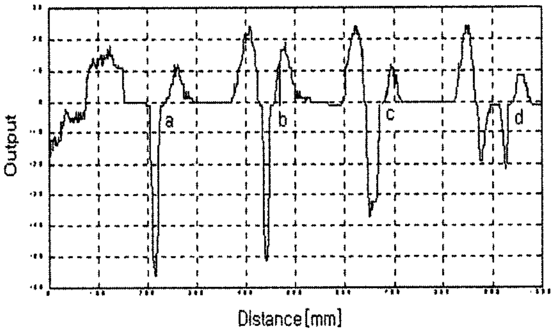
Figure 4.1(b) shows the detecting result to be measured by the implemented system. As a result, it can be easily seen that the output of detector is nearly proportional to the number of broken wires.

Furthermore, the output of edge of broken wire demonstrates such property shown in Figure 2.3(b). And the response of abrasion part is also shown good sensitivity. Electromagnetic instrument to inspect wire defects may be affected by the location of sensor and defect so that its output would sometimes be including external noise or disturbance. However, it is obvious that severe faults can be distinguished from the output.

As described in Section 2.3, the type of fault or its length in wire rope tester may affect the response of detector. Therefore, it is an important issue to assess faults from the obtained data, and sometimes it may give any common information. In general, the assessment for faults based on measurement data would be dependent upon several parameters such as magnetic intensity, length between magnetic poles, sensor direction or structure of sensing head.



(a) shapes of length of broken wires



(b) testing result

Figure 4.2 Performance of length of broken wires

One experiment to verify property for changing length of broken wire results in Figure 4.2. To show such performances, an another test wire rope is prepared shown in Figure 4.2(a). This sample is cut off 2 wires and lengths of broken wires are 5(a), 10(b), 20(c) and 50(d)[mm]. For the implemented sensing head in Section 3.2, if length of broken wire is increased, the peak value of response is reduced as illustrated in Figure 4.2(b). Especially, when the length is over 50[mm], most magnetic leakage flux is generated near to the broken location while the magnetic flux at the center of broken region is rather reduced than other place. Finally, it should be careful attention in analyzing fault from testing results.

4.2 Field Test

To examine some properties for the implemented detecting system, a field test is performed in situ for aged wire ropes installed in an apartment. This was a wire rope with about the elapse of 2 years. Figure 4.3 illustrates a testing result for a wire rope.

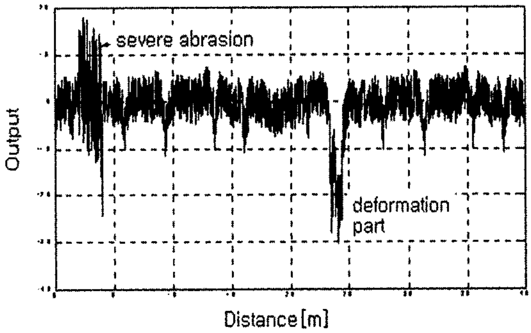


Figure 4.3 An example of field inspection result

We can know that the field testing result shown in Figure 4.3 has many perturbations compared with the result in Figure 4.2 because the air gap between the sensing head and the testing wire may change more than that in case of laboratory experiment. As the filed test result, there may exist click output signals nearly to the position around 2~4[m] distance and one undershoot signal located about 23~24[m]. The first one may be a part of severe abrasion and the last would be a serious defect such broken wire or deformation.

According to visual inspection from the test wire rope, it was verified that there was a little abrasion due to contacting wire rope with sheave around the position 2~4[m] and nearly at 24[m], a deformation is found.

Through several tests in situ, it would be necessary to improve sensing sensitivity and to establish stable output for reference sample, but the developed system shows an effective result for assessing any severe fault such as broken wire, abrasion or deformation.

5. Conclusions

Wire ropes are often used in critical load carrying applications where no redundancy or fail-safe feature is incorporated in the design. Especially, wire rope failures in operating elevator may lead to extensive property damage and serious injury to nearby personnel. Failure detection of wire rope requires fundamental knowledge of wire rope construction, rope behavior, properties of faults, sensing and signal processing method. In this paper, the development of a new fault detecting system of aged wire ropes in elevator incorporating Hall-effect sensors to detect flaws such as abrasion, broken wire, corrosion and deformation is described. To design a utilized detector as a portable instrument, sensing part with Hall-effect sensor, analog signal processing unit, and programs are considered. Experiments and field testing results for the implemented detecting system are also given. As a result, it may be verified that the detecting system has good efficiency for inspecting faults of aged wire ropes in service.

References

[1] R.A. Egen, Nondestructive testing of wire rope, 9th Annual Offshore Technology Conference, pp. 375~382, Huston, 1977.

[2] B.G. Marchent, An instrument for the non-destructive testing of wire ropes, Systems Technology, No.29, pp. 26~32, 1978.

[3] H.R. Weischeldel, The inspection of wire ropes in service: A critical review, Material Evaluation, Vol. 43, No. 13, pp. 1592~1605, 1985.

[4] Inspection Regulation, Korea Elevator Safety Institute, 1995.

[5] F. Kitzinger and J.R. Naud, New developments in electromagnetic testing of wire rope, CIM Bulletin, Vol. 72, No. 806, pp. 99~104, 1979.

[6] K. Hanasaki and K. Tsukada, Estimation of defects in a PWS rope by scanning magnetic flux leakage, NDT & E International, Vol. 28, No.1, pp. 9~14, 1995.

[7] Regulations for the Industrial Safety and Health Act, Ministry of Labor

[8] E. Kalwa and K. Piekarski, Design of Hall-effect sensors for magnetic testing of steel wire ropes, NDT International, Vol. 20, No. 5, pp. 295~2301, 1987.

[9] H.R. Weischedel, Electromagnetic wire rope inspection-resolution is important, Material Evaluation, pp. 1297~1310, 1998.

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