STUDY ON THE MAGNETIC HEAD LENGTH OF INDUCTIVE COIL SENSOR FOR STRANDED WIRE ROPE TESTING

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ABSTRAK : *Wayar kabel digunakan secara meluas dalam aplikasi industri seperti elevator, lif, kereta kabel dan kren. Maka, adalah perlu untuk sentiasa melaksanakan pemeriksaan ke atas wayar kabel tersebut untuk mengelakkan sebarang kemalangan disebabkan kerosakan dalaman. Selain daripada pemeriksaan visual, kaedah ujian tiada kerosakan (non destructive test method) digunakan untuk memeriksa keadaan wayar kabel ini. Pengesan Hall (Hall sensor) dan pengesan fluxgate (fluxgate sensor) adalah contoh terkini yang digunakan untuk mengesan kerosakan dalam wayar kabel. Dalam penyelidikan ini, kombinasi dua magnet kekal dan gegelung pemeriksa adalah digunakan sebagai gegelung induktif. Gegelung induktif ini adalah sejenis pengesan pasif dengan struktur ringkas. Pada keadaan normal, nilai fluks adalah tetap. Maka, pengesan wayar kabel ini hanya akan mengeluarkan isyarat apabila keretakan berlaku sepanjang wayar kabel tersebut. Isyarat ini dianalisis berdasarkan perubahan fluks berbanding masa. Untuk mendapatkan isyarat yang lebih tinggi, kesan perubahan saiz mata gegelung pemeriksa telah dikaji dan dibincangkan dalam penyelidikan ini.*

ABSTRACT : Wire ropes are used widely in industrial applications such as elevators, lift system, cable car system and crane services. Therefore, there is an obvious need to perform tests on the integrity of these wire ropes to avoid any fatal accident due to its internal flaw. Apart from visual inspection, the non destructive test methods are available to check the condition of these wire ropes. Hall sensor and fluxgate sensor are examples of the recent methods for wire rope inspection. In this paper, a combination of two permanent magnets and a search coil are used as inductive coil. This inductive coil is a passive type sensor with a simple structure. Under normal condition, the value of flux linkage is constant. Thus, wire rope sensor will induce a signal when there is any crack occurring along the wire rope. This signal is analyzed based on the rate of change of flux due to time. To obtain a higher signal, the effects of head size of the search coil was studied and discussed in this paper.

KEYWORDS : Wire rope, magnetic head length, non destructive testing, flux leakage, noise threshold, S/N ratio.

INTRODUCTION

Wire ropes are used widely in industrial applications such as elevators, lift system, cable car system and crane services (Park and Park, 2002). Due to the long duration usage, surface as well as the internal of wire ropes may have defects (Zawada, 1999). Therefore, there is an obvious need to check the condition of the wire ropes regularly to avoid any fatal accident due to its internal flaw (Moriya *et al*, 2004). Apart from visual inspection, the non destructive test methods are available to check the condition of these wire ropes (Moriya *et al*, 2004; Placko and Dufour, 1993). Various methods have been used for wire rope testing such as eddy current, ultrasonic and radiographic. However, each method has some drawbacks in their application. For example, an eddy current method works on the transformer principles, making this method complex. Ultrasonic testing requires sophisticated and high end instrument for signal detection and processing. Radiography method is very hazardous and requires competent personnel for safety inspection. (Prakash,1980).

Alternatively, a wire rope sensor based on electromagnetism principles has been developed. This sensor is a passive type sensor and its structure is very simple. It is made up of three main components; sensor head (magnetic circuit), signal conditioning circuit and signal processing circuit. The sensor will only produce a signal when there is a relative movement between the sensor head and the tested wire rope. Signal processing is one of the main objectives of the experiments that were done to obtain optimum speed control and head size of the inductive coil of this wire rope sensor. An analysis was done using Finite Element Method (FEM) followed by sets of experiments to study the effects of head length on the performance of the sensor. Finally, it was observed that head size of 2mm produces the highest flux linkages.

OPERATING PRINCIPLES OF INDUCTIVE COIL SENSOR

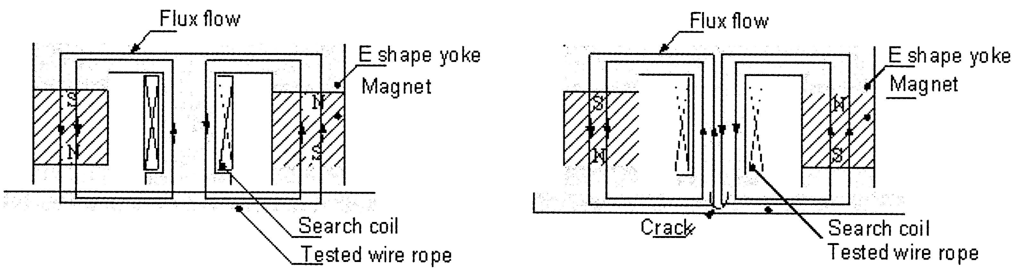
Basic principles and structure of sensor

The design of the inductive coil is based on a modeled flux linkage under normal and crack condition. This is the most important procedure as it determines the dimension and materials used for the sensor structure. Figure 1 shows the flux linkage of the modeled design sensor head under normal and crack condition. Under normal condition, the flux flows from the first permanent magnet on the left yoke to the second permanent magnet on the right as shown in Figure 1(a). There will be a very small leakage of flux flowing through the search coil since the magnetic resistances across the search coil are very high. Conversely, under crack condition, a large number of flux leakages are flowing through the search coil since the magnetic resistance is reduced due to the existence of crack as shown in Figure 1(b). Therefore, a significant difference of flux linkage between normal and crack condition exists. The rate of change of flux, Φ due to time will induce a voltage that indicates the cracks condition.

According to Faraday's Law, a static magnetic field produces no current flow, but a time-varying field produces an induced voltage which is known as electromotive force (emf) within a close circuit, which causes current flow. Michael Faraday discovered that the induced voltage is equal to the time rate of change of the magnetic flux linkage by the circuit. As for the case of an inductor coil, where the electric wire makes N turns, the induced voltage or emf produced within the close magnetic circuit can be expressed as follows :

$$V_{emf} = -\frac{d\lambda}{dt} = -N\frac{d\Phi}{dt} \quad (1)$$

Where V_{emf} is the induced voltage or emf, N is the number of turns of the coil in the circuit and Φ is the magnetic flux through each turn.



(a) Flux flow under normal condition (b) Flux flow under crack condition

Figure 1. *Model of flux linkages under normal and crack condition*

Detection system of sensor

The basic principle of this sensor is the rate of change of flux due to time that occurs between the metal and air gap. As discussed briefly in the introduction, the inductive coil of this sensor is made up of two permanent magnets and a search coil arranged in E-shape core or yoke. The signal induced by the sensor is then fed into the filter amplifier circuit for signal conditioning purposes. It is then passed into signal processing circuit (ATMEL 8535) before it can be displayed. This signal processing circuit is programmed to ensure that the detection signal must be above the noise threshold set by the system. Figure 2 shows the whole block diagram of wire rope sensor.

When there is a relative movement between the inductive coil and the tested wire rope, an induced signal will be produced. This signal is based on the rate of change of flux due to time. Then, this signal is fed into an active band-pass filter circuit. This band-pass filter has a narrow bandwidth of 30Hz to 50Hz. The filter circuit is a major part to be considered because from initial analysis, the induced voltage directly from the sensor head contains noise mainly of lower frequency (< 30Hz) and higher frequency (> 50Hz). The induced voltage frequency of wire rope crack is in the range of 30Hz ≤ freq ≤ 50Hz. After that, the signal is passed through a variable amplifier with a gain of 100, 150 and 450 before it is fed into a microcontroller circuit to be processed. Two important parameters are taken into account in this study; the effects of magnetic head length and amplifier gains. The most efficient result will be produced if the voltage induced has a very high peak above the noise threshold.

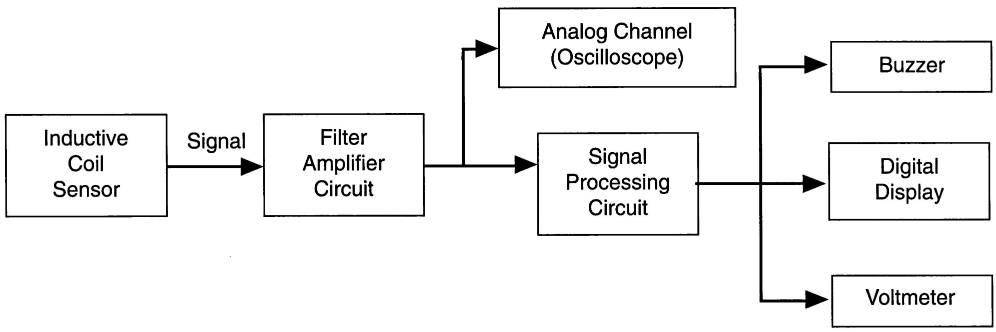


***Figure 2.** Block diagram of wire rope system*

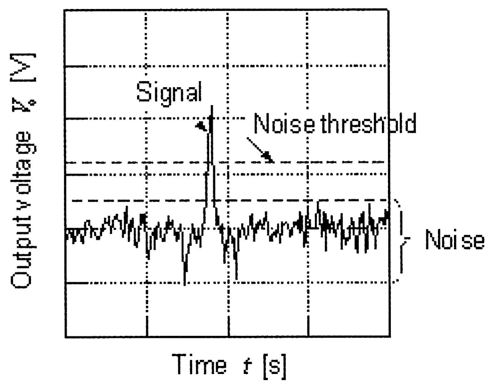


***Figure 3.** Noise threshold setting in the signal processing circuit*

Figure 3 shows an example of noise threshold setting in the signal processing circuit. From the experiments done, the values of noise peak to peak are very high which is 2V. Thus, to avoid noise from affecting the performance of the sensor, noise threshold was introduced. This was done by taking data during normal condition where crack does not exist. Noise threshold is set by calculating the noise average peak to peak value. Its function is to make sure that small detected signal can be traced regardless of noise level. Therefore, the effects of magnetic head length have been studied to improve the performance of the sensor.

SIMULATION ON EFFECTS OF MAGNETIC HEAD LENGTH TO INDUCTIVE COIL SENSOR

2-D simulation of this wire rope sensor was done using Finite Element Method (FEM). Figure 4 shows modeling of wire rope sensor used in this analysis. The wire rope used in this analysis is designed as a piece of plate with 2mm crack and it varies every 5mm from -75mm to 75mm as shown in Figure 4. The value of air gap used in this analysis is 30mm, similar to the calculated magnetic resistance of the inductive coil sensor. Modeling specifications used in this analysis is shown in Table 1.

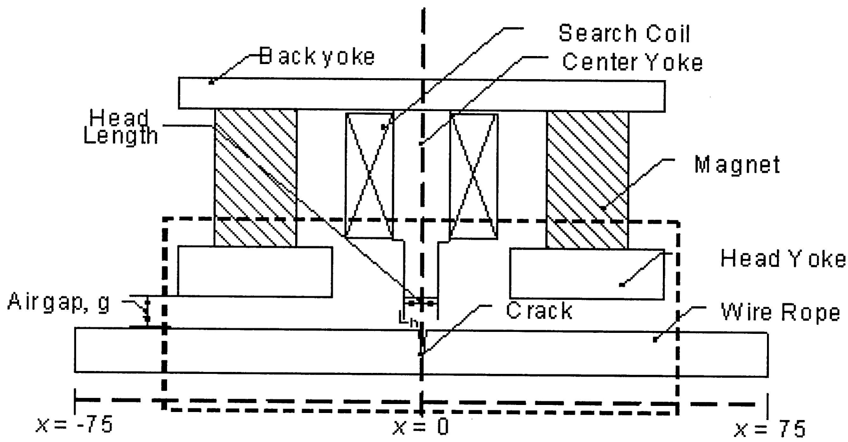


***Figure 4.** Modeling of wire rope sensor*

Table 1. Modeling specifications used in the simulation

Item	Material
Back yoke	Mile steel
Magnet	NEOMAX32
Search coil	Coil turn = 10000
Center yoke	Mile steel
Head yoke	Mile steel

Numbers of flux flowing through the search coil have been observed during normal and crack conditions. Figure 5 shows two examples of flux flowing during normal and crack condition. It is done by setting the crack displacement from -75mm to 75mm and initialized at 0. The value of flux linkages for every crack displacement are recorded and plotted as shown in Figure 6. Maximum values of flux linkages, ϕ_{max} for every head length configuration are then plotted into the graph, Flux linkages, ϕ (Wb) versus Head Length, L_h (mm) as shown in Figure 7.

The value of ϕ_{max} will decrease as the head length increased. This is due to the reduced air gap between the head length and the head yoke, causing the magnetic resistance between them to decrease. Figure 8 shows the difference of flux flow when the head length are 2mm and 18mm and it is taken partially from the whole modeled wire rope sensor marked as dotted line in Figure 4. For example, as shown in Figure 8 (a), there is no flux leakage through the head yoke when the head length is 2mm due to high magnetic resistance between the head length and head yoke. However, small number of flux have leaked through the head yoke out from the center yoke (Figure 8 (b)) when the head length is 18mm since the gap between head length and head yoke has been reduced, leading to the reduced magnetic resistance between them. Therefore, from the analysis done using FEM, it shows that the smallest head length which is 2mm produces the highest flux linkages as shown in Figure 7.

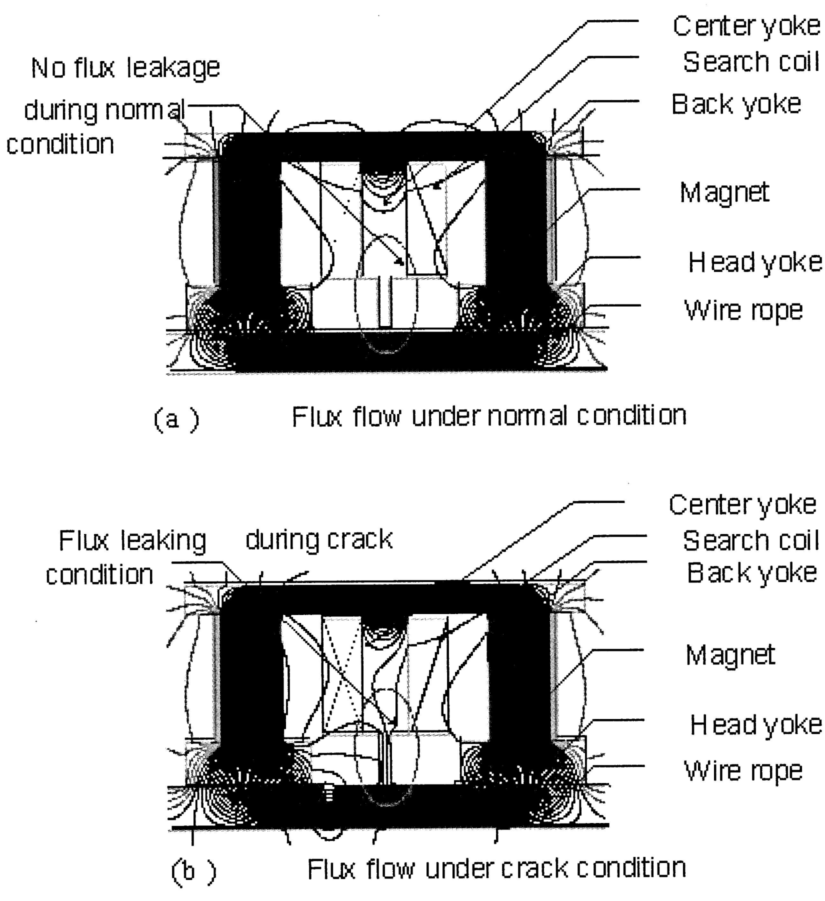


Figure 5. *Flux flow under normal and crack condition*

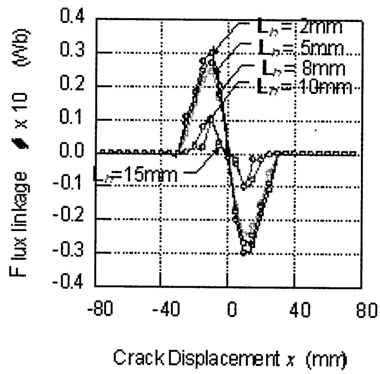


Figure 6. *Graph of maximum flux linkages, ϕ (Wb) versus crack displacement,* **x** *(mm)*

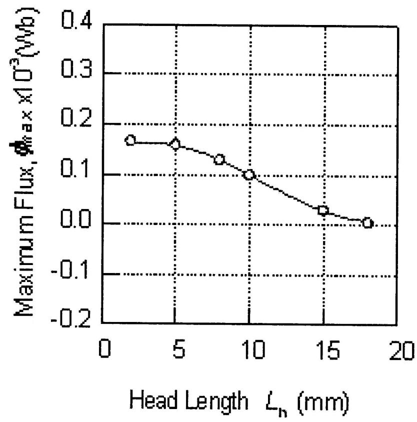


Figure 7. *Graph of maximum flux linkages, ϕ_{max} (Wb) versus head length,* $\mathbf{L}_h$ *(mm)*

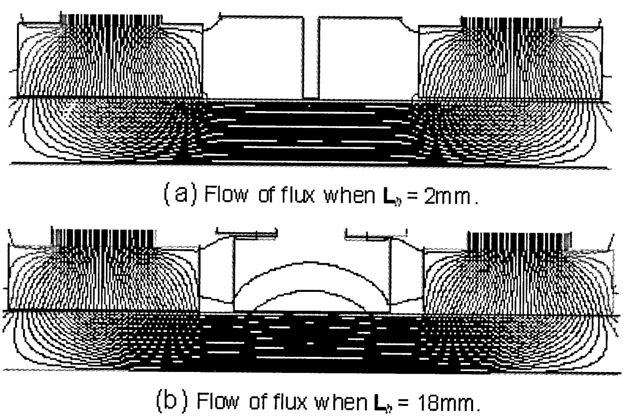


Figure 8. *Effects of head length, L_h to the flow of flux in the wire rope sensor*

EFFECT OF MAGNETIC HEAD LENGTH TO INDUCTIVE COIL SENSOR

A set of experiments were conducted to observe the performance of the sensor under different lengths of the head size. Five sets of different length head size were used in the experiments : 2 mm, 5 mm, 8 mm, 10 mm and 15 mm. Configuration of this magnetic head length were chosen randomly to fit the gap between the center yoke and the head yoke. The value of amplifier gain used in these experiments is fixed to 150. Results shows that smaller length of head size produces the most efficient result, with a very high peak above noise threshold. Length of head size that produces efficient result is 2mm.

Experiment setup

For performance observations of this wire rope sensor, two parameters were selected; the effects of magnetic head length and amplifier gains. This is done to obtain the best specification of the wire rope sensor that will produce higher induced voltage.

A few parameters need to be set constant to get the accurate experiment results. The distance D, which is the moving path of sensor, needed to be set constant throughout the whole experiment. The starting point and ending point is set to be the same for all experiments. The sensor is moved by using a weight connected to the sensor with a pulley. The free falling distance of the weight has to be more than the distance of sensor head moving path, D. The sensor will have a constant acceleration along its moving path which is the gravitational force acceleration, approximately at $9.81\ ms^{-1}$.

Experiments to observe the performance of this sensor were carried out. The diameter size of the wire rope used is 5mm and moving distance of the sensor along the wire rope is set to be at 50cm. For crack detection purpose, three cracks were created along the wire rope.

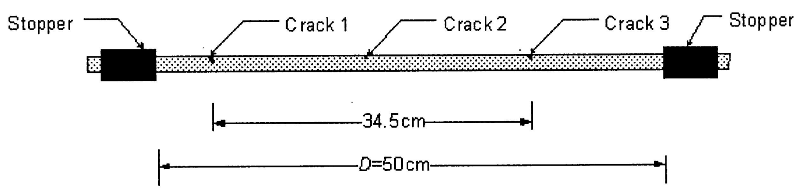


Figure 9. *Tested wire rope used in the experiment*

Figure 9 shows the physical layout of the tested wire rope used in the experiment. Crack 1 and 3 are severe cracks whereas crack 2 is a minor crack. These hairline cracks were done by scratching the surface of the wire rope to different depths. The purpose of creating different level of cracks is to observe and study the sensitivity of the wire rope sensor. This is an important factor that should be considered to improve the performance of this sensor.

Magnetic head length variation effects

Three induced voltages indicated three different level of cracks on the tested wire rope. Experiments show that a higher induced voltage indicates the crack is more severe. A severe crack will have more leakage flux, ϕ through the coil and increase the rate of change of flux. Therefore, the induced voltage will also increase according to Faraday's Law. Graphs of the experiments done with different sets of magnetic head length are shown in Figure 10. Results show that the highest signal was produced by the sensor when the magnetic head length used is 2mm as shown in Table 2.

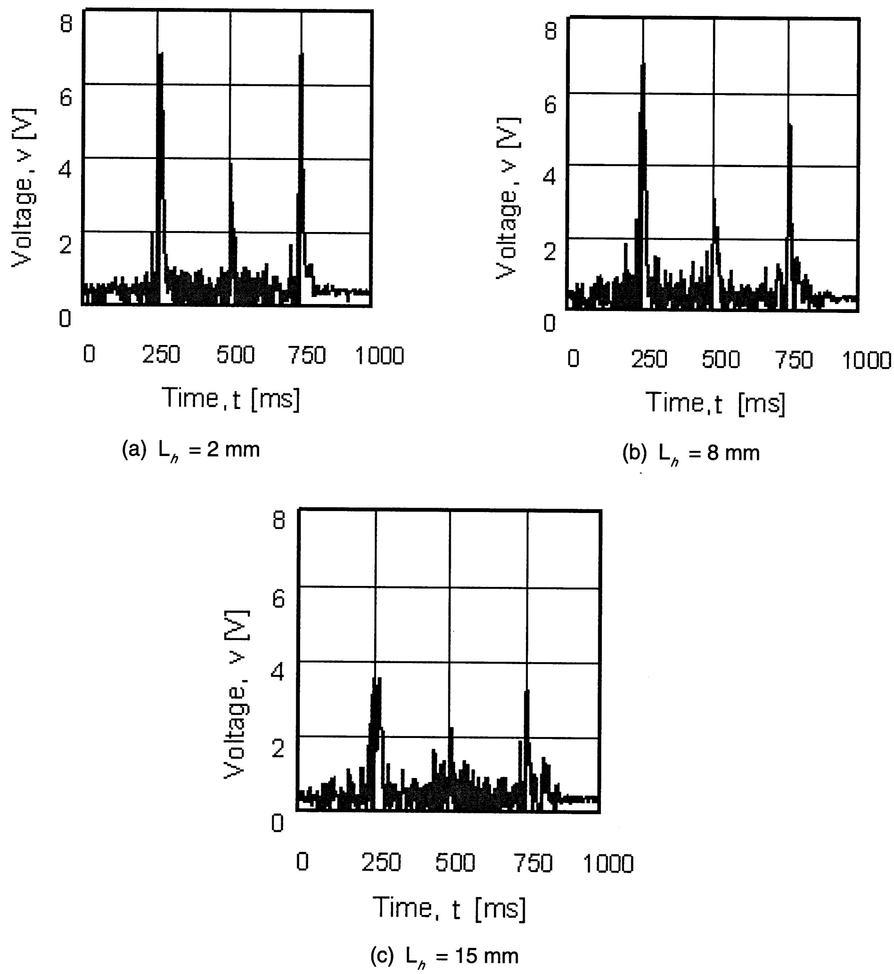


Figure 10. *Graph of induced voltage versus time for* L_h *= 2 mm,* L_h *= 8 mm and* L_h *= 15 mm.*

Table 2. Reference crack voltage with magnetic head length

Magnetic Head Length, l (mm)	Reference Crack Voltage, V_r (V)
2	6.80
5	5.36
8	5.04
10	3.44
15	3.12

Signal-noise analysis

Signal-noise analysis is necessary to evaluate the induced voltage signal and the effects of noise. Therefore, the definition of induced voltage signal and noise are important. Figure 11 illustrates the method used in the signal-noise analysis from the graph of induced voltage signal. Figure 11 shows the signal-noise analysis is based on induced noise threshold, ΔVn and its induced voltage signal of reference crack, ΔVi. The reference crack is chosen in the analysis. The reference crack chosen is crack 3 on the wire rope. The crack signal, ΔVc is defined as the difference between ΔVi and ΔVn (Robinson, 1974). Referring to the noise threshold of the signal, the ΔVn is determined based on the maximum induced ΔVn along the graph. A simple mathematical expression is derived as shown below :

$$\Delta Vc = \Delta Vi - \Delta Vn \tag{2}$$

Initially, the signal-noise analysis for each magnetic head length configuration was conducted with fixed amplifier gain at 150. Figure 12 shows the comparison of graph plotted for simulation and experimental result. As the magnetic head length increases, the difference between the induced voltages of reference crack, ΔVi and the noise threshold, ΔVn is reduced. This implies that the sensitivity of the sensor reduced as the magnetic head length increases. From the signal - noise analysis, it can be summarized that the magnetic head length 2mm at amplifier gain 150 shows the optimum performance of the sensor.

Simulation result and the experimental result were compared as shown in Figure 12. The value of ϕ_{max} was obtained when the head length is at 2mm, decreasing as the head length increased.

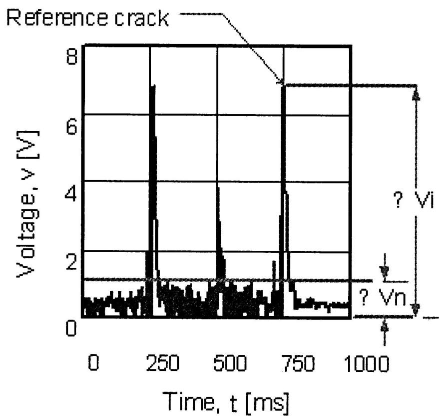


Figure 11. *Method for signal-noise analysis of sensor*

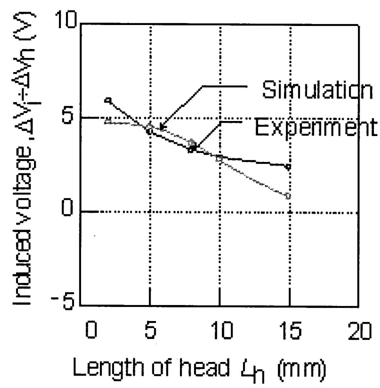


Figure 12. *Graph of comparison between simulation and experiment*

CONCLUSION

The wire rope sensor based on electromagnetic principles is an alternative technique to check the condition of those wire ropes used extensively in industry. This sensor is a passive type sensor and it consists of three main components such as sensor head, signal conditioning circuit and signal processing circuit. Sets of experiments and simulation using FEM were done to observe the performance of sensor. Results from the simulations show that the maximum flux linkages decreased as the head length increased. Results from the experiments produced slightly similar result with the simulation. The value of induced voltage decreased as the head length increased. Comparison was made and experimental results imply results from the simulation done using FEM. Signal analysis is also done based on the results from the experiments. The signal-noise analysis shows that optimum performance for sensor is at the 2mm magnetic head length configuration with 150 amplifier gains.

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