Inspection of Internal Impairments of Steel Wire Rope by Electromagnetic Detecting Method

By

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In this paper, to contribute to the development and the practice of the electromagnetic inspection of the internal impairments of steel wire ropes, the method which was employed in this study and the results of some fundamental experiments are stated.

The outline of some field inspections which were carried out with the trial equipment are shown, and the result of the visual inspection obtained by breaking up an actual rope and the electromagnetic inspection record of the identical part are correlated and discussed.

Further, the procedure of estimation of present strength of a wire rope by electromagnetic inspection are stated. Taking this procedure, we can estimate the present strength with reasonable high accuracy, and it has been recognized that the electromagnetic inspection is an effective method for the good maintenance of steel wire ropes.

1. Introduction

The internal impairments of steel wire rope are hard to detect by any outside inspection because of its complex structure. Accoreingly, it is very difficult to presume the present strength of the wire rope which is in service. On the other hand, the corrosion or the breakdown of internal wire hastens the propagation of damage of adjacent wires due to the notch effect, and under insufficient care for the rope maintenance, it brings about the accidental breakdown of the wire rope.

To prevent the serious accident above mentioned, it is put in practice that the rope which has got the prescribed duty period or has carried out the prescribed transportation of the total amount, is renewed, though it sometimes is liable to make a premature renewal because many replaced ropes have retained sufficient strength as a result of the later break test, say in a large majority, 95% or more, of new rope.

In Japan, the so-called ABCDE (Abrasion, Broken wire, Corrosion, Deformation, Eccentricity etc.) method has been introduced by Dr. Nishioka[1], and it is

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well known as a valuable method which enables us to estimate the present strength without any special instrument, however, it is mainly based on experience. Hence, it requires us to use considerable effort to be skilled in it and also it takes a fairly long time to inspect the long wire rope.

Therefore, to eliminate the wastefulness and to utilize the wire ropes without anxiety, a certain testing method which produces the information of internal defects and which enables us to estimate the present strength for any rope while it is being placed in actual service, has been desirable.

Consequently, the various methods of electromagnetic testing of steel wire rope have been investigated by many investigators in the world[2~9], and recently, several rope testers have appeared on the market*. The rope inspecting equipment was not put to use around 1960 in Japan when we started to study this problem in spite of the much effort by many investigators in this field. In these circumstances, the appearance of up-to-date electrical instruments is releasing some of difficulties which have been concern in this method, and accordingly, we have started research into the practicability of electromagnetic method since 1962[10~17].

In this paper, we state the results of research for some subjects and the circumstances of practical inspection.

2. Principle and Subjects for Consideration

The electromagnetic inspecting method of wire rope which is employed in this investigation is based on the principle mentioned below.

The wire rope under testing moves through the exciting coil which is set around the rope and carrying a sufficient intensity of direct current. In another way, the wire rope moves through the magnetic pole rings which are excited electrically.

Accordingly, a certain length of the passing rope is strongly magnetized to the state of its magnetic saturation while each passing part of the rope is within the exciting range. When the sections including any impairments pass through the range, a certain amount of magnetic flux in the rope is forced out from the surface corresponding to the cross section, and it changes locally the distribution of the surrounding magnetic flux.

By the other detecting coil which is prepared near the wire rope in the middle part of magnetizing range, the magnetic anomalies on the surface are detected which are due to the local impairments of the wire rope, and its defects are inspected.

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* Rope Testing Equipment: Brandt, West Germany.
Structographe: Legpa, France.
Dual Frequency Electromagnetic Rope Tester: McPhar Mfg., Canada.
Steel Rope Wear Indicator АИ-3, ДИ-3, Steel Rope Flaw Detector ДСК-У: USSR.

In order to detect the local impairments, even in the case of the interior defects, by the leakage flux on the surface of the rope, it is necessary that all the effective sectional area should be strongly magnetized up to the magnetic saturation or to a condition close to it. So as to perfectly realize this condition, it is necessary that direct current should be applied and sufficient magnetomotive force should be derived. Accordingly the copper amount of magnetizer becomes considerably large, however, any trouble caused by natural magnetism or other magnetic history is completely beside the question.

But from the point of view of practical use in the actual places using the wire rope, it is natural that the reduction of the size and weight of the device should be desired. Hence it becomes important to decide the values of the necessary exciting force for the practical use of the wire rope in the various sizes and structures.

In regard to the detecting coil which takes out effectively the leakage flux near the surface of the wire rope as the detected signal, two partial coils are used in the differential connection in this study. But it is necessary that the determination of the number of their winding and sizes should be investigated in various ways from the point of practical use and performance.

3. The Magnetization of Wire Rope

The results of former studies about the decision of the magnetomotive force which is necessary to magnetize the wire rope to the degree of the sufficient strength to put it to practical use, have not been so well expressed till recently, for instance, it is only presented that as to the wire rope of 30 mm in diameter, magnetomotive force of 10,000∼40,000 Ampere-Turns is required for common size of the exciting coil[4),8)].

This necessary magnetomotive force corresponds with the sectional area of the wire rope, and of course it is also affected by the condition of the path of the exciting magnetic flux. Among all, the air gap in the magnetic circuit especially dominates over its value.

In case where there is such a magnetic pole as an iron core and yokes, this air gap is identified with the gap between the magnetic pole and the surface of rope, and in the case where that exciting coil is wound co-axially round the rope, the external space near the coil mainly corresponds to this air gap conclusively as the return path of the magnetic flux. In either way, the moving wire rope is magnetized through this air gap, and therefore the condition of this air gap dominates the efficiency of magnetization.

In the method that uses magnetic poles, it is possible to make this air gap smaller, but on the other hand we need to restrain the lateral oscillation of the wire rope and the adhesion to the magnetic pole by means of guide rollers, while in the method that uses the co-axial coil, troubles originated in oscillation of the wire rope is smaller and we do not need to restrain the wire rope, though the reluctance in the exciting magnetic circuit increases.

Moreover, for the various effects by the different specification of the coil, the determination of the magnetomotive force which is necessary for the magnetization of the wire rope must be done according to the working state. According to our results that have been investigated to compare with the states of magnetization by both methods mentioned above, we are employing both the direct magnetizing method by the co-axial coil as well as the yoke type exciter having a large air gap to a certain extent which has sufficient efficiency without losing the merits of the magnetization[11].

We have done the experiment mentioned below to investigate the performance of detection of the defects of the internal wire when the exciting current is changed.

At first, as shown in Fig. 1, an steel wire of 3.2 mm in diameter (that is 8.04 mm^2 in sectional area), is inserted at the center of the steel pipe of 48 mm in outer diameter and 43 mm in inner diameter (that is 357 mm^2 in sectional area).

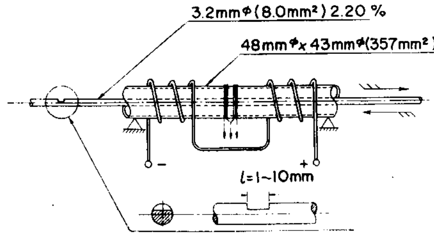


Fig. 1. Notched Wire passing through a Fixed Steel Pipe.

This steel wire has a joint which is spliced with a piece of non-magnetic material in this section after being cut off once. Still more, it has various notches in several parts of it.

If only this steel wire is pulled longitudinally in the fixed steel pipe, we can make a condition equivalent to the case of a steel pipe having various interior defects with the same appearance. In this case, the largest change of the sectional area becomes about 2.2% when the rejoined part of the internal wire passes.

An example of the record obtained by this method is shown in Fig. 2. From this we see the gradual increase of the output voltage of the detecting coil as the exciting force increases. This reason is that the difference between the inner diameter of the steel pipe and the diameter of the steel wire is considerably large, and the magnetic saturation of the steel wire in the central space is not gained without difficulty. But the detecting voltage to the various notches of the steel wire shows a good proportion to their respective sectional areas.

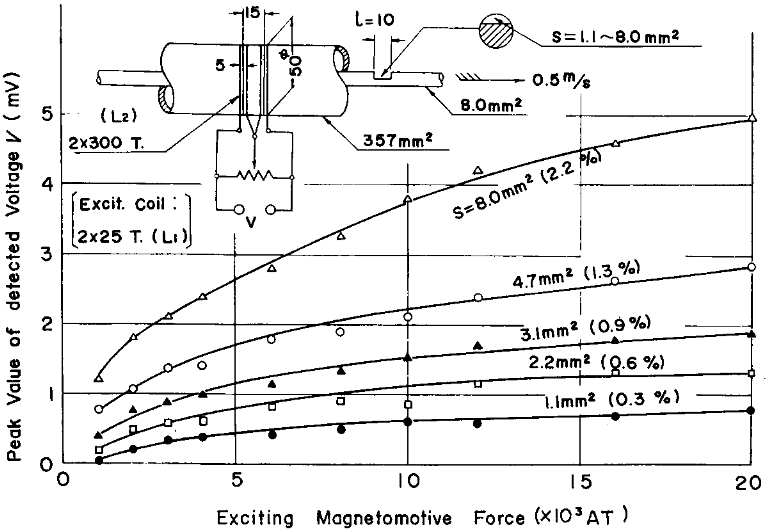


Fig. 2. Relation between Exciting Magnetomotive Force and Voltage induced in Detecting Coil.

In order to know the adequate value of the exciting force thoroughly, we employed a method of the criterion by turning our attention to the ripple which is included in the exciting direct current. Namely, if the ripple voltage between the terminals of the exciting coil is put as V_1, the wave form of the ripple V_1 being included in the exciting current is beginning to change in consequence of the change of the permeability with the state of the magnetization of the test piece. (Cf. Fig. 3).

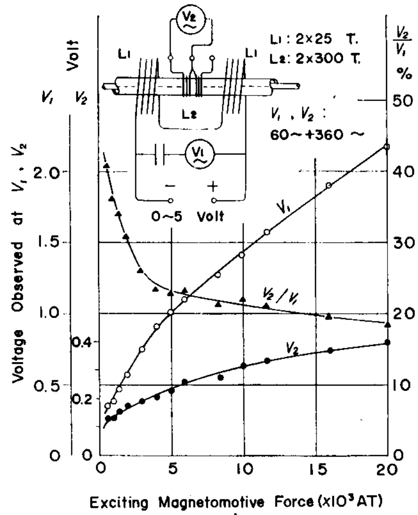


Fig. 3. The Result of Experiment to judge the Magnetic Saturation of Test Piece.

If the component of alternating voltage which is induced in the detecting coil by the mutual inductance through the iron core, when the iron core is used as the test piece, is put as V_2, the changes of V_1 due to the state of the magnetization of the test piece can be shown to be magnified by V_2.

So far as V_1 and V_2 are observed respectively, their changes due to the intensity of the exciting current are not particularly clear. But if the values V_2/V_1 are plotted, the distribution of it is shown in Fig. 3. According to this figure, when the exciting force gets to about 3,000 AT, we can guess that the state of the magnetization of the test piece changes remarkably. So it can be considered that the practical values of the exciting force can be decided by the values V_2/V_1.

We have done a series of experiments about several kinds of wire ropes. And from the result that we have considered the detecting faculty of the defects within the bound of the exciting forces below their respective imaginary saturation exciting forces to them, the detected outputs corresponding to the different notches in their test pieces have turned out to be proportional to their respective sectional areas of the notches, even if the values less than the exciting force bringing the magnetic saturation are used.

Though these values are about 10 AT per sectional area 1 mm^2 of the test pieces according to our exciting coil, the exactness of it is not particularly required as was mentioned above. Therefore, leaving the exciting current heavy to a certain extent, we not only do not need the constancy of the voltage of the power supply, but also have only to adjust it according to the rise of temperature of the coil.

In case of the use of the co-axial exciting coil, the coil must be wound on the bobbin split into two pieces on the spot, taking the wire rope at the actual place as the axis, it is desirable that it has possibly a less number of winding. Accordingly, it is required to handle a heavier exciting current, and the power supply is required to have special functions somewhat.

But in recent years the silicon rectifiers with large capacity and small in size, have been developed, so we can conveniently utilize the heavy direct current of low tension by using them.

As the yoke bringing the magnetic poles close to the wire rope is not used in the magnetic circuit in this method, the fluttering of the intensity of magnetization due to the lateral vibration of the wire rope is slight. Moreover, as it is not entirely in contact with the wire rope, we have little anxiety about any noise picked up electromagnetically due to the unavoidable vibration of the wire rope which passes though with considerable speed.

The rectifier circuit of the power supply is fitted for the heavy current of low tension and is the 6-phase half wave rectifier with the double star 3-phase winding being able to expect the little ripple content. In spite of the exciting coil having not enough inductance, the ripple in the exciting current can not come to be a troublesome interferrence in practical use. In this case, as the frequency of this ripple is six times as much as the frequency of mains and has a fair difference to compare with the frequency (100$\sim$200 c/s) of the signal induced by the defects of the passing wire rope, it is very favourable for the transmission and treatment of the signal. But when there is an unevenness of the winding of the transformer or rectifier elements, or the phase unbalance in the mains, an undesirable component belonging to the fundamental frequency appears and makes the signal-noise ratio of the records worse. So we should be careful. The layout of our apparatus is shown in Fig. 4.

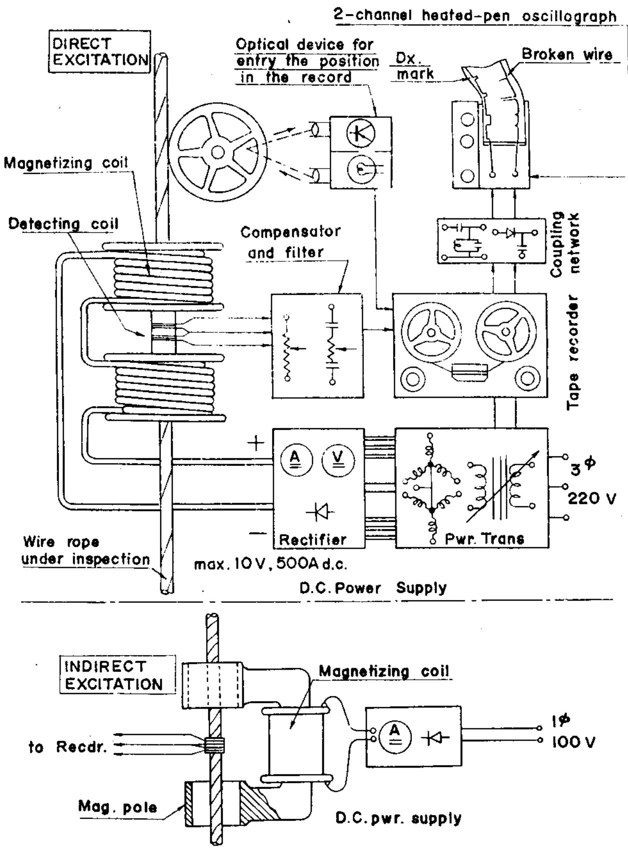


Fig. 4. Outline of the Equipment with Dircet Excitation and Indirect Excitation.

4. Detecting Coil

The coil which detects the defects of the wire rope, as a matter of course, the nearer it is to the surface and the more the effective number of windings is, the higher signal voltage it generates. But depending on the amplitude of the lateral oscillation of the wire rope at the practical speed, it is necessary that the gap between the inside of the coil and the surface of the wire rope should be larger somewhat.

As for the form of the detecting coil, we have investigated which is better, winding round the wire rope or setting the prepared coil of the divided form on the surface of the wire rope. As the result of this investigation, at this stage of this study, we have decided to adopt the co-axial coil with the rope. Therefore, like the co-axial exciting coil, it has a demerit that we have to wind up the coil on the spot at the field and that we can not find in which strand of the rope the defect is from the result of the detection. But it takes only ten minutes for us to wind up this coil, and it is superior in this respect that the sensitivity and accuracy of the detecting defects are good, that the bad influence due to the lateral oscillation of the wire rope is slight and that the electrical treatment at the stage of the recording can be easily done because of its structure being simple.

The detecting coil, as it is shown in Fig. 5., has two fundamental forms. And it is able to perform the signal having minimum noise by neutralizing the noise of the same phase due to the vibration of the wire rope and the ripple in the exciting current, by the treatment that the two partial coils are connected differentially.

The number of turns, the diameter, the thickness and the length of coil are important factors to decide its performance. From the results of basic experiments done on this respect, the proper limits in practical dimension of detecting coil are naturally fixed for the respective size of wire ropes. Though the induced electromotive force of coil is in proportion to the effective number of turn, considering that a distribution of local magnetic field originated in impairment, and considering the limits in coil dimension, in order to increase the number of turn within its extent, we have to use fine electric wire, and then it is hard to handle, and also the impedance of coil increases, and it adds to difficulties on signal transmission. Considering these above-mentioned facts, the coil we have used on field application in this study is wound on a hard vinyl divided bobbin with its inner diameter not in contact with moving rope, and on the surface of the bobbin, two grooves of 5 mm width and 2 mm depth are cut at intervals of 5～30 mm in order to let the coil nearer to the surface of the rope, in order to keep stability of the widings. In the grooves, enamel covered copper wire of around 0.2 mm thick is respectively wound about one hundred times.

As we show at the left side in Fig. 5., the special character of this detecting coil depends on the combination of the polarity of each partial coil and the way of connection.

As shown in Fig. 5., we assume the signal voltage which is induced in the partial coil by local impairment in the rope V, and assume the noise voltage in the partial coil which is caused simultaneously in both coils by pulsation of exciting

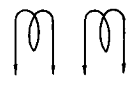
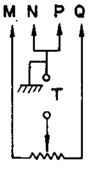
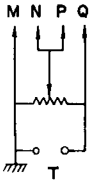
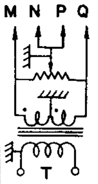
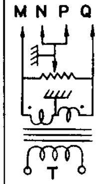
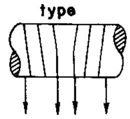
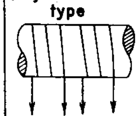
Type of detecting coil	Electromotive force induced in the detecting coil			External connetion (I-IV) and output terminal voltage T. n : Winding ratio of coupling transfomer			
	Kind and cause	Terminal voltage based on N or P 		I	II	III	IV
		M N	P Q	M N P Q  T	M N P Q  T	M N P Q  T	M N P Q  T
Symmetrical type  M N P Q	Signal voltage due to local defect	$\frac{V}{O}$ or	$\frac{O}{V}$	$\frac{V}{2}$	V	nV	nV
	Noise voltage due to change of magnetic flux common to both coils	E	E	E	O	O	2nE
	Noise voltage due to electrostatic induction (including the lead wire)	e	e	e	O	O	2ne
Asymmetrical type  M N P Q	Signal voltage due to local defect	$\frac{V}{O}$ or	$\frac{O}{V}$	$\frac{V}{2}$	V	nV	nV
	Noise voltage due to change of magnetic flux common to both coils	E	E	O	2E	2nE	O
	Noise voltage due to electrostatic induction (including the lead wire)	e	e	e	O	O	2ne

Fig. 5. Co-axial Detecting Coils and their Connections.

current or by the osciallation of wire rope *E*, and assume the noise voltage in the partial coil which is caused by stray magnetic flux or electrostatic induction *e*; what is superior in the signal-noise ratio is the connection II, or the connection III with symmetrical coils.

Comparing these two, as for connection II; though a circuit is simple, the connection II is asymmetrical against the grounded side, and therefore if the tape-recorder is put some ten meters from the detecting coil, this transmission line is liable to sustain some interferrences. On the other hand, as for the connection III is this case; as the transmission line is balanced type in this connection, it can transmit for more distance, and we can expect a certain voltage gain with coupling transformer; but it has also a demerit that when magnetic shielding of the transformer is inperfect, it causes some noise disturbances by stray flux near there. After considering these we have adopted the connection II at present.

At least we are able to make equal the number of windings of both partial coils, but it is very difficult for us to make entirely equal the wound-up shape. For this reason, unbalances in inductance and/or stray capacitance of the coil remain. And since the unbalance may be produced also accoring to the state of the disposition of the ferrous materials such as the constructing member of winding shaft near the coils, it is necessary for us to compensate these unbalances at the actual place when the detected signal is recorded into the magnetic recording tape.

If we let the condenser to the compensation of the reactance part in addition to the compensation of the resistance part by means of each potentiometer shown in Fig. 5., and after we reduced the unbalance voltage to a minimum by adjusting them to each other, we had better. The schema of compensator accommodative to both types of detecting coils is shown in Fig. 6.

Though this compensation is done, the noise ratio of the signal which was recorded on the magnetic tape is generally not enough yet. So it is necessary for us to modify the wave form to get practical records. On this problem we are about to describe in 5.

Assuming that the number of windings of the detecting coil is 300 turns respectively for two partial coils, it has enough sensitivity to the wire rope moving with tolerable low speed (several centimeters per second). On the contrary, for the detection of the defects of the wire rope with the speed 5 m/s or more such as the vertical shaft winding rope, it has become clear that it has enough sensitivity even at 2×50 turns in its number of winding.

We think that the detecting coil is enough in this form for general moving ropes. But a pair of semi-circuiar coils which enables us to prepare them before they are set, has also many merits in practical use. These are under investigation.

In the next case, the space between two detecting coils has much influence on its performance. As it is shown in Fig. 7., assuming that we take the respective diameter of the two partial coils d and the space between two centre of them p, as the value p/d comes to be large, the detected voltage v comes to be large too. But as

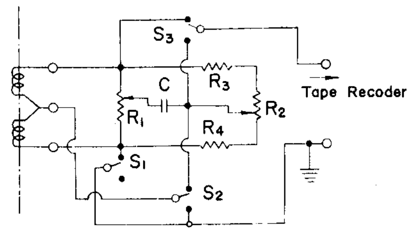


Fig. 6. Balancing Circuit for the Incidental Undalance in Detecting Coils.

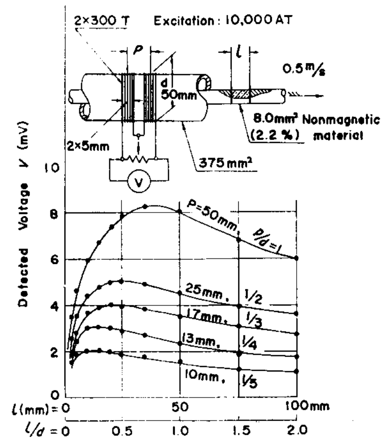


Fig. 7. Change of Detected Voltage Depending on the Shape of Detedting Coil and the Gap of Broken Wire.

this fact is closely related to the performance to eleminate the noise in the same phase and "resolving power" on the finding of impairments, to make the value p/d large is not always proper. Though the detecting coil in the practical use in this study takes the value p/d about 1/5, the loss in sensitivity due to it can be fully made up by the gain of the amplifier. Next, the broken wires in ropes have commonly some spaces between the opposite edges.

In Fig. 7. we take this space l and show the change of the detected voltage due to the change of l/d together with p/d above mentioned. Though the unevenness in the sensitivity to the various values p/d are comparatively slight when the values p/d are small, it is influenced considerably by the small values l/d. This fact can be thought to be an inevitable one not only in the method in this study, but also any methods in the electromagnetic testing for the wire rope. But by turning our attention to the fact that the wave forms of the voltage impulse V induced in the detecting coil are different according to the magnitude of the values l/d and carrying out the adequate modification of the wave form, we have been able to get a result thought to be sufficient in practical inspection.

5. The Recording of the Detected Voltage

When we carry out the detection of the defects of the wire rope by the apparatus above mentioned in this study, if the wire rope passes through the coil at the speed 2～3 m/s, we can get the detected voltage of 2～3 mV in average to a piece of broken wire. And as this voltage is decided by the state of the distribution of the leakage flux due to the broken wire and the passing speed to the detecting coil, it is shown as an impulse having a duration of 1/100～1/200 sec. It can be thought that one of the reasons that this method has not been publicized is that any recording apparatus which has enough responsibility to such a signal voltage of this kind, and that is able to get the long record which needs several ten minutes in case of the inspection of long wire rope and which can be used conveniently and economically at the actual place, has not been publicized before.

In this study, in considering the voltage sensitivity, the frequency characteristics, the recording time and economical stand point, we at first record the signal voltage wave from the detecting coil on the magnetic recording tape as the primary record and have decided to get the visible chart at the same time or on another day from the magnetic tape as a secondary record. In this case, in the respect to both the voltage sensitivity and frequency range, we can fully make use of the common tape recorder without any additional wave modulation, but as it is desirable that we enter the distance from the standard point of the wire rope at the same time, we use a double channel tape recorder.

Among the merits which the use of the magnetic tape recorder like this has as the primary recorder for the detection of the defects of wire rope, the next items can be thought to be noticeable however it will be attributable to the performance of the tape recorder itself as the data recorder.

(1) As compared with other long time recording apparatus, it can deal with a wide range of signal frequency. So we can inspect the wire rope almost with regular driving speed and raise economically the frequency of periodic inspection.

(2) As it can reproduce the necessary parts of the records at any time in the form of a voltage wave, we can change the total length or part of it into a chart by shortening or magnifying, accommodating the reproducing speed to the characteristics of the secondary recorder or to the destination of the analysis. The edition and the duplication of it are also easily done.

(3) When we do not need the chart and the wave form analysis, we can know the outline of the grade of defects by only the acoustical output being able to be picked up in the midst of the inspection.

When data recorded on the magnetic tape is desired to be converted into the visible chart, the recorder is usually played back at reduced tape speed, because a pen oscillograph has a maximum frequency responsibility of about 100 c/s. And it is convenient to eliminate background noises by using a coupling amplifier with a non-linear characteristic or setting a lower limit arbitrarily to voltage being handled, and to write out only the required data by preference by neglecting a slight sectional change that has a negligible effect on the strength of a wire rope.

The detected signal voltage taken out from the magnetic tape has been transformed in wave form before it is led into a pen oscillograph for the purpose of improving the definition of the oscillograph and keeping a good correspondence of the recorded wave forms to a loss of the sectional area of a wire rope and the gap between broken wires (this influences the duration of the signal voltage). It is a matter of course that care should be given to a change of the frequency of the signal voltage caused by changing the play back speed of the tape.

In the field recording, the length of the visible recording paper has ranged from 1/10 to 1/6,000 the actual length of a wire rope according to the object of inspection.

6. Inspection of C.B.C. Wire Rope.

The wire rope which is used in C.B.C. (Cable Belt Conveyor) has few changes of driving speed and few oscillations due to the driving and can be inspected easily through the total length and, as compared with the shaft winding rope and the inclined shaft one, can be used continuously till considerable decay can be recognized. For this reason it can be said that any C.B.C. wire rope is the one to which we can apply this electromagnetic inspection most effectively and conveniently.

We are about to give the outline of the C.B.C. with which we carried out the electromagnetic inspection for the wire rope and are about to state the outlook of the inspection and the result which was obtained and the method to calculate the strength of the wire rope according to the result of the inspection.

6.1 C.B.C. that the inspection for the wire ropes was done, and its wire ropes

Table 1. The electromagnetic inspection of a C.B.C. wire rope.

Place	Oshima Coal Mine, Matsushima Coal Mining Co. Near the surge wheel of No. 4. C.B.C.	
Length of C.B.C.	2,150 m	
Average inclination	12°	
State of driving	120 m/min, surge wheel type with wrap angle 6π, 2×400 kW $\times$ 720 r.p.m.	
Capacity	400～450 ton/hr	
Strength of new rope	Actually 77.6 ton; Certificated 76.2 ton, 36 mmϕ, 4.99 kg/m. Cf. Fig. 8	
Width and weight of belt	920 mm, 27.4 kg/m	
Date of renewal of rope	Left side	Right side
	Oct. 9, 1961.	Dec. 3, 1962.
Date of inspection by this method	Jul. 21, 1963.	Mar. 24, 1963. Jul. 21, 1963. Dec. 20, 1963.
Length of rope inspected	4,400 m (overall)	
Speed of inspection	2 m/s	
Magnetizing coil	2×25 turns, 100 mm^2 rubber covered cable	
Magnetizing current	100～400 A (5,000～20,000 AT)	
Detecting coil	2×100～300 turns, 0.08 mm E.C.C. wire	
Chart length	1/20～1/4,000 of the actual rope length	
Date of replacement of rope	Aug. 25, 1963.	Dec. 20, 1964.
Date of break up	Aug. 31, 1963.	
Result of break test	See Table 2.	

This C.B.C. is being worked for transportation of coal and debris in the Oshima Pit of Matsushima Coal Mining Co.

The outline of the C.B.C. and the wire rope, and the outlook of the inspection are shown in Table 1. and Fig. 8.

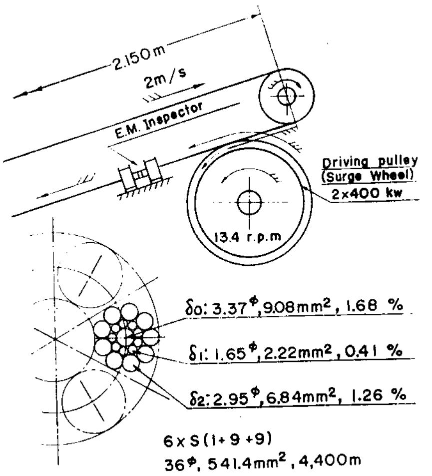


Fig. 8. The Electromagnetic Inspection of C.B.C. Wire Rope.

6.2 The procedure of inspection

After we wind the coils we adjust ech centre lest their coils should come into contact with the wire rope at all and fix them. Then, after we made sure of the polarity of magnetization between two exciting coils if they are used together, and the electromagnetic balance of the two defferential detecting coils could be taken, the wire rope may be driven.

When the wire rope makes one round to the initial situation, the inspection finishes. In this mine, it takes about forty minutes due to the regular rope speed.

6.3 The record of the inspection and comparison with the result of having broken up the wire rope

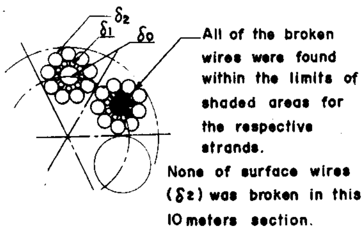
An example of the chart written from the magnetic tape by heated-pen-oscillograph is shown in Fig. 9. This is also the Table for the comparison, the figure of the record which was obtained by doing the electromagnetic inspection of the defects of the one side wire rope of this C.B.C. with the result that later we cut off ten meters of the wire rope and took it out and broke it up. There were no parts of the broken wire which were known by exterior observation to this extent.

The situations of the broken wires which were found by breaking up the respective strands are shown from the upper line to the lower line in this figure. The situations of the broken wires which are shown in this figure are expressed by the mark having magnitudes proportional to their respective sectional area of the wires.

The seventh line in this figure is the diagram which superposed the marks of defects through all the strands, and also in case of the strands being different, the signal which existed in the same situation on the rope is shown to be added.

The ninth line shows the chart drawn by the oscillograph corresponding to

Wire	δ_0	δ_1	δ_2
Diameter (mm)	3.37	1.65	2.95
Sectional area (mm²)	9.08	2.22	6.84
Number of wires in a rope	6	54	54
Aggregate sectional area (mm²)		541.4	
Rope strength (ton)		77.6	



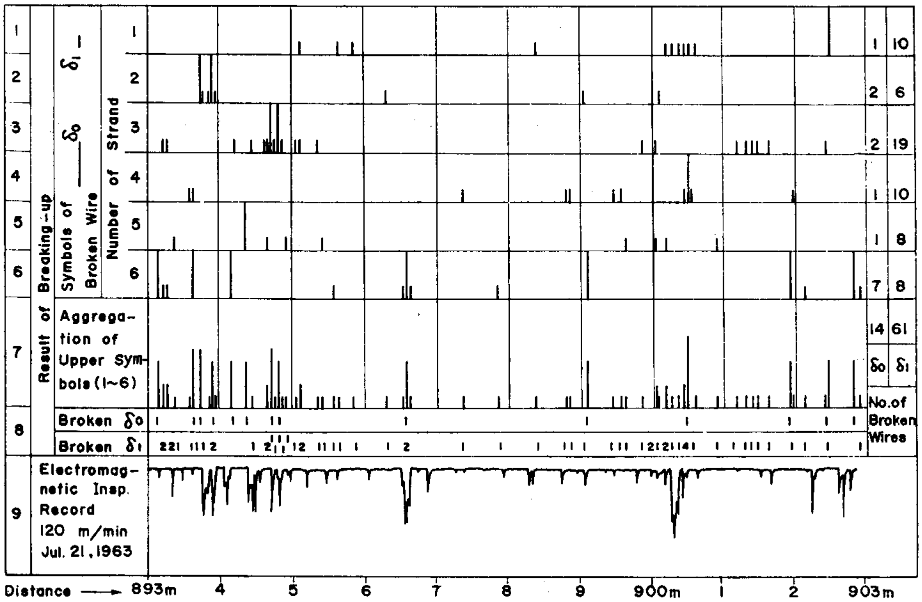


Fig. 9. The Result of Breaking-Up Test given to a Part of C.B.C. Wire Rope and the Electromagnetic Inspection Chart of the Same Part.

this extent of the wire rope, and this is proportionate to the diagram on the seventh line.

But as perfect coincidence can not be seen to extend to the detail of the wave form, we have investigated this. Consequently, this is due to the next reason.

First of all, that after we carried out the electromagnetic inspection of the defects of the wire rope, they went on with the transportation of about 130×10^3 tons for about one month before we took away and broke up this, after we stopped the driving and took away the wire rope and took it to outside of the adit.

At the second, when the necessary part of this is cut off, the elongation of the wire rope changes, that when we break up the rope of ten meters into all the wires, as the form of twist changes and the apparent length increases about 10%, the measurement of the distance in the parts of the broken wire is accompanied by a considerable inevitable error, they are the major reasons we can think.

Now taking into consideration the increase and the error of the situation of the defects after the inspection carried out, when we make the amplitudes and the forms of impulses of the inspected record correspond to the grade of broken wire, we can get the standard of estimation as is shown in the eighth line in this figure. But, as the oscillogram shown in the ninth line includes the characteristics of non-linearity of the amplifier and the recorder and all the other peculiar conditions, it is the effective standard of estimation only to the records which were obtained for this rope in this method.

6.4 The estimation of the strength of the wire rope by the electromagnetic inspection record

As the result of the above mentioned, as we could find the contrast between the inspection record and real impairments of this wire rope, we have done an estimation of the present strength of the rope by the electromagnetic inspection record of the other parts of the same wire rope.

Fig. 10. is the diagram which was shown to make the wave form on the chart of the other parts (near the broken up part shown in Fig. 9.) correspond to a kind of wire and the number of broken wires according to the standard of Fig. 9.

Well, though the wire rope bring about the loss of the strength at their sections by the breaking of its wire, the broken wire is in charge of the strength of the rope again in other distant situations.

This, as widely known, is due to the friction of the adjacent wires being attributed to the twist of wires in the rope. Consequently, the strength of the wire rope comes to be affected by the degree of the concentration of impaired wires in it. From the result of the break test for the rope which was shown in Fig. 10. we have presumed to what range of the length of this rope the breaking of the wire affected. According to our presumption we could see that the total sectional areas of the broken wire among around three pitches of the twist of strand and the decay of the strength of the rope had a proportional relation in this wire rope. This total sectional areas of the broken wires among three pitches is shown in their respective part in Fig. 10.

We selected further several parts in this wire rope and determined their sectional areas by the same treatment as in Fig. 10. The present strength of their respective parts which we estimated from that values and the measured strength of their respective parts by the break test are shown in Table 2.

In this Table, at first, in order to know the loss of the strength due to only the wear of the rope, we weighed out a certain part of the rope and calculated,

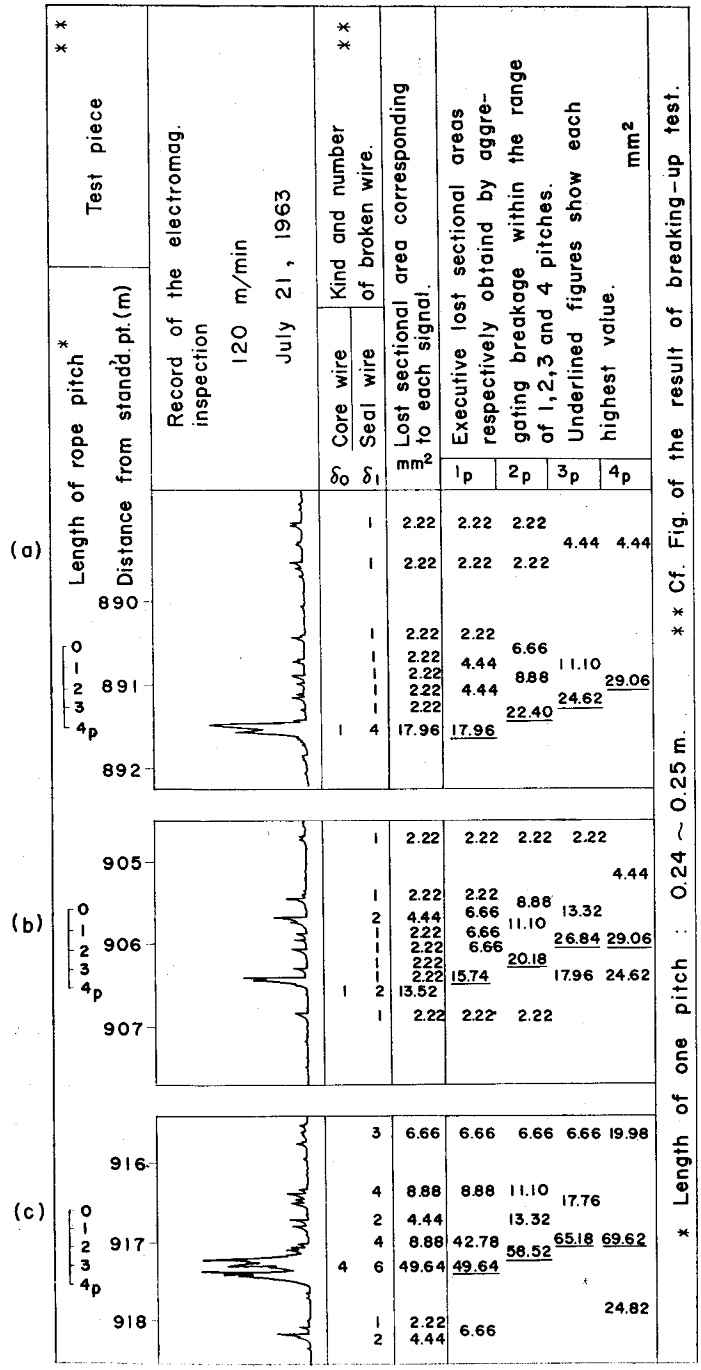


Fig. 10. Estimation of Lost Sectional Areas from the Inspection Record.

Table 2. Actual rope strength and estimated strength from inspection record.

Test piece		quoted 1 pitch ①			quaoted 2 pitches			quoted 3 pitches			quoted 4 pitches			⑤ Actual rope strength by break test (ton)	Remarks
No.	Position of test piece	② Loss in area mm²	③ Lost strength ton	④ Present strength ton	② mm²	③ ton	④ ton	② mm²	③ ton	④ ton	② mm²	③ ton	④ ton		
1	866–869	15.7	2.8	61.9	18.0	3.2	●61.5	24.6	4.3	60.4	26.8	4.7	60.0	61.2	
2	871–874	29.3	5.1	59.6	47.2	8.3	56.4	63.9	11.2	●53.5	63.9	11.2	●53.5	54.6	
3	891–893	18.0	3.2	61.5	22.4	3.9	60.8	24.6	4.3	60.4	29.1	5.1	●59.6	59.7	Fig. (a)
4	905–907	15.7	2.8	61.9	20.2	3.5	61.2	26.8	4.7	60.0	29.1	5.1	●59.6	59.7	Fig. (b)
5	916–918	49.6	8.7	56.0	58.5	10.2	54.5	65.2	11.4	53.3	69.6	12.2	●52.5	52.8	Fig. (c)
6	930–933	15.5	2.7	62.0	20.0	3.5	61.2	22.2	3.9	60.8	24.6	4.3	●60.4	58.0	piece 893~903 m was to be broken up
7	946–949	18.0	3.2	61.5	24.6	4.3	60.4	29.1	5.1	●59.6	47.0	8.2	56.5	60.0	
8	1,047–1,049	15.7	2.8	61.9	22.4	3.9	60.8	24.6	4.3	●60.4	44.8	7.8	56.9	60.0	
9	4,150–4,154	33.7	5.9	58.8	33.7	5.9	58.8	54.1	9.5	●55.2	54.1	9.5	●55.2	56.0	

①: Assuming the affecting range of broken wires on the rope strength respectively within the rope length of 1, 2, 3 and 4 pitches.
②: Executive lost sectional area obtained by aggregating breakage within the range ①.
③: ② multiplied by strength of wire (175 kg/mm²).
④: Subtracted the lost strength 12.9 ton* due to even wear from the value of strength 76.2 ton, and still more subtracted the lost strength due to breakage shown in ③.
⑤: Carried out at Kokura Factory, Tokyo Seiko Co. Ltd; Oct., '63. (ref. 38/145).
* : By calculation of weight diminution in 10 meters piece:

New rope: 4.99 kg/m=4.77 kg wire+0.22 kg hemp core.
Used rope: 4.20 kg/m=3.98 kg wire+0.22 kg hemp core.

Weight diminution of steel wires:

$(4.77-3.98)/4.77=16.6\%$ equiv. to 12.9 ton.
77.6 ton-12.9 ton$=64.7$ ton.

and subtracted the strength from the value of the new rope. Then, we showed the presumptive existing strength after subtracting again the loss of strength that we multiplied the specific strength of wire by the above mentioned sectional areas of the broken wires. From those results we can find that the aggregated lost sectional area within the range of three or four pitch length does affect the strength of the rope.

6.5 The progression and increase of the impairments accompanied by the use

Before we broke up the wire rope (the left side) which we mentioned in 6.3 and 6.4, we carried out the electromagnetic inspection of the opposite wire rope (the right side) in this C.B.C. about three times a year and could successively get

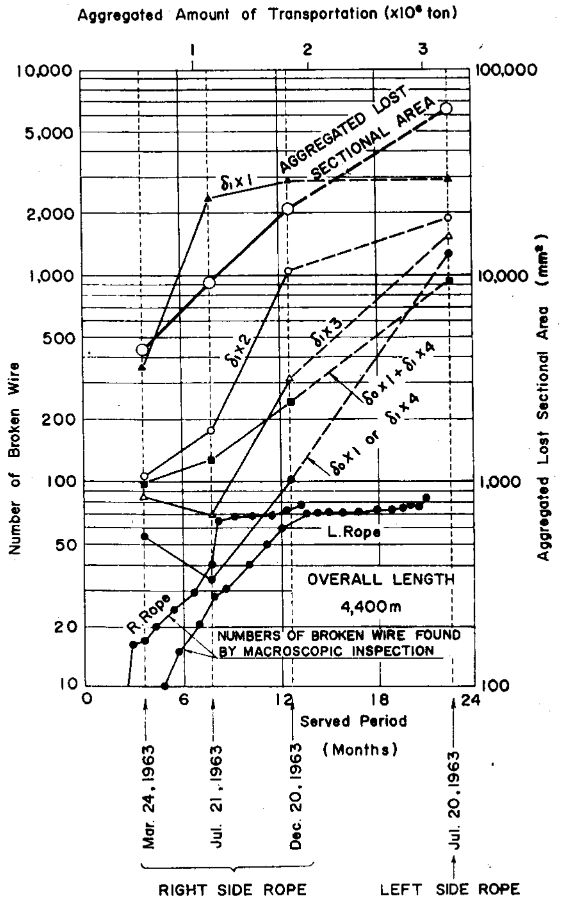


Fig. 11. Increase of Defects with the Lapse of Time of Service. (C.B.C.).

the records of the same rope. In the midst of it as we did the resolving investigation of the left side rope which had been used already, as was above mentioned, we could presume the state of increase of the defects by applying its result to the inspection records of the right side rope. The inspection method every time is the same one as we mentioned in 6.2.

We made the comparison and classification according to the result of 6.3 and 6.4 (Figs. 9 and 10), and if we draw the result that we summed up the total impairments extending over the whole length of the record, it becomes just as Fig. 11.

In this figure, "$\delta_1=1$" is the number of times of the detected signal impulse that the wire δ_1 was regarded to have a broken part, and "$\delta_0 \times 1$ or $\delta_1 \times 4$" shows the uncertain breakage that we cannot know which wire the broken one is, because the sectional area of δ_0 is nearly four times as large as the one of δ_1. Though the number of signals of the broken wires of "$\delta_1 \times 3$" and "$\delta_0 \times 4$ or $\delta_1 \times 1$" which were recorded on July 21 decrease as compared with the one of the inspection record on March 24, this can be thought to be for the several pieces of the wire which were the concentrated broken wire of δ_1 in March as was above mentioned, since their respective broken section dispersed with the transportation till July, the rate of concentration in one section of the wire rope decreased. This can be supported by the remarkable increase of the number of the broken wires δ_1 in the record in July and from the circumstances of the increase of the aggregated lost sectional area in the overall length of the rope as was shown also in this figure.

The successive record of this right side wire rope is three times one, that is to say about one year in the period of the use, but as the resolving result of the left side wire rope mentioned 6.3 is equal to the point shown at the situation of 22.5 months in this figure, we can presume that later the right side rope also traces the process shown by a broken thick line and the defects increase.

As the aggregated lost sectional area shows the exponential increase to the lapse of used time or the total amount of the transportation, if we determine the limit of the use of a rope by such aggregated sectional area, we can fairly accurately find the time which exceeds this limit by the method now mentioned. Further, in this figure, we showed the superficial numbers of the broken wires which were found by the periodic naked eye inspection.

7. Conclusion

We carried out the electromagnetic inspection of the impairment of the wire rope respectively on several occasions by using the trial equipment above mentioned, and we discussed the inspected record obtained from the wire rope of a Cable Belt

Conveyor as a typical example of the application of this mthod.

From the result we compared this inspection record with the resoving result of the wire rope, and we could make sure that this method was suitable to get the effective record of non-destructive testing.

This method, however, is effective only to the local impairments of the objects having the broken wire and local wear but has not a sensitivity to the longitudinal mild sectional change so-called thinning, of the test piece. This is obvious from the principle of this method. In this respect, we are studying the method that we will carry out a continuous measurement of the effective sectional area of the wire rope by using the large alternating exciting force, since the development of the inspection method for the stay rope or guy rope and for the rope-end is desired also.

But the most important thing is the estimation of the present strength of the wire rope, and as the test pieces of the field experiment which have been used till now, excluding the C.B.C. rope, were the ones that there were scarcely defects both in the inspection record and from the resolving result and had almost the same strength as the new wire rope, the data which can connect the inspection record with the present strength of the wire rope directly to the various kinds of wire ropes have not been obtained sufficiently in the present stage.

As was mentioned in 6., the successive records which were got by carrying out this to a wire rope priodically become very valid data for the good maintenance of the wire rope, and we can easily presume the present strength of the same kind of wire rope by comparing the result of the break test with the resolving result.

Acknowledgement

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