Design of inductive sensors for magnetic testing of steel ropes

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The design and operating principles of four inductive sensors for magnetic testing of steel ropes are presented. The magnetic concentrators can maintain the same shape as in Hall-effect leakage flux sensors, but the output signals of the inductive sensors are quite different and depend on the speed of testing. Although the inductive sensors are not as versatile as Hall-effect sensors, they are simpler in operation and can still find applications, especially in the initial and middle stages of the deterioration of the rope.

Keywords: inductive sensors, magnetic testing, steel ropes

Wire ropes are inspected periodically from the time they are installed until the time they are replaced. The frequency of inspection depends on the character and magnitude of the load carried by the rope and the condition of the rope. The closer to the replacement time of the rope, the more frequently and accurately the inspection has to be performed. The test procedure should be able to determine the actual strength of the rope and whether or not the replacement criteria apply.

Instruments recently used for nondestructive testing of wire ropes most frequently use the DC magnetic method[1]. Among them various types of sensors have been applied which measure the major flux in the magnetic head or the leakage flux around the rope[2]. It has been shown that leakage flux sensors provide better sensitivity and quantitative resolution and can eliminate the need for measurement of the major flux[2,3]. In these sensors inductive coils or Hall generators can be used as transducers of the magnetic field into the electric signal. Applying Hall generators, a velocity-independent signal can be obtained and the output signal is proportional to the measured magnetic parameter. Depending on the shape of the magnetic concentrators used in the sensor, different components of the magnetic flux density can be measured and different output signals can be received for the same defect[4-6].

The signal coming from the inductive sensor is a first derivative of the magnetic flux with respect to time and only defects which cause significant and sudden variations of the leakage flux can be determined[6]. Numerous measurements of the magnetic field inside the magnetic head have shown that single broken and missing wires, single abrasions and corrosion patches are accompanied by such variations[4]. These kinds of defect usually occur in ropes exposed to intensive cyclic loads and in ropes which are generally well protected against corrosion. When the defects become multiple and the deterioration of the rope approaches the replacement criteria, inductive sensors are less accurate and must be supported by another type of sensor[8,9]. This suggests that periodic tests of the rope in service can be performed with inductive sensors, which are less expensive and easier to operate, rather than with Hall generators. Only at the end of the rope's service do more accurate, but also more complicated, instruments with Hall-effect sensors need to be used.

Magnetic concentrators used for Hall-effect sensors[5] can also be applied for inductive sensors. The output signals will depend on the value and distribution of the radial and tangential components of the magnetic flux density around the rope. Another advantage of inductive sensors is that they do not require a supply of energy and their output signals maintain the zero-level outside the defect.

The inductive sensor for the radial component

Figure 1 shows the principle of the inductive sensor, which allows one to measure the average value $B_R$ of the radial component at a distance $R$ from the axis of the rope. The cores of the inductive coils are placed between two concentric rings surrounding the rope and acting as magnetic flux concentrators.
The electromotive force induced in the $i$th inductive coil can be found from Faraday's law as

$$ e_i = -z_i \frac{d\phi_i}{dt} $$

(1)

where $z_i$ is the number of turns in the $i$th coil, $\phi_i$ is the magnetic flux passing through the core of the $i$th coil and $t$ is the time.

All the coils have similar parameters and are connected in series. Hence the output voltage of the sensor is

$$ E = \sum_{i=1}^{n} e_i $$

(2)

where $n$ is the total number of coils in the sensor; $n$ is an even number because the sensor has two halves which are hinged together for easy positioning of the sensor on the rope under test.

The total magnetic flux passing through all the cores of the coils is

$$ \phi_c = \sum_{i=1}^{n} \phi_i $$

(3)

In this design of sensors the magnetic flux $\phi_c$ is proportional to the average value $B_r$ of the radial component:

$$ \phi_c(x) = k_c B_r(x) $$

(4)

where $k_c$ is the coefficient of concentration of the magnetic flux, which depends on the design and material of the rings and cores, and $x$ is the position of the defect with respect to the centre of the magnetic head measure along the 'x' axis, parallel to the axis of the rope.

Then the output voltage of the inductive sensor for the radial component is

$$ E(x) = k \frac{d\overline{B}_r(x)}{dt} $$

(5)

where $k$ is a new coefficient which depends on the design of the whole sensor. Since

$$ \frac{d\overline{B}_r(x)}{dt} = \frac{d\overline{B}_r(x)}{dx} \frac{dx}{dr} = \frac{d\overline{B}_r(x)}{dx} v $$

(6)

where $v$ is the speed of the rope passing through the sensor, the output voltage becomes

$$ E(x) = kv \frac{d\overline{B}_r(x)}{dx} $$

(7)

Figure 2a shows samples of the average magnetic field density $B_r$ for various broken wires, while Figure 2b shows the corresponding output signal $E$. The peaks of the signal occur at one side of the zero-level for short defe
while at the middle of the long defect the signal displays a zero-value.

The double inductive sensor for the radial component

Figure 3 shows the sensor consisting of two of the inductive sensors shown in Figure 1. The two assemblies (I and II) are placed at a distance $2c$ from each other and positioned at the centre of the magnetic head. Their outputs are connected in series, so that the output voltage of the whole sensor is

$$E(x) = E_1(x) + E_{II}(x)$$

Using Equation (7) and taking into account that both assemblies are at a distance $c$ from the centre of the magnetic head, the output signals from the assemblies are

$$E_1(x) = k_1 v \frac{d\vec{B}_1(x+c)}{dx}$$
$$E_{II}(x) = k_{II} v \frac{d\vec{B}_1(x-c)}{dx}$$

where $k_1$ and $k_{II}$ are the sensitivities of assemblies I and II respectively. Assuming the same construction of both assemblies we have

$$k_1 = k_{II} = k$$

It was shown by Kalwa and Piekarski[9] that outside the centre of the magnetic head the radial component $B_r$ maintains the initial level $B_{r0}$ (which is not affected by defects in the rope) in addition to the variations $B_{r1}$ caused by the defects in the rope:

$$B_{r1}(x) = B_{r0} + B_{r1}(x)$$

Then

$$\vec{B}_1(x+c) = B_{r0}(-c) + \vec{B}_{r1}(x+c)$$
$$\vec{B}_1(x-c) = B_{r0}(+c) + \vec{B}_{r1}(x-c)$$

Fig. 4 - Signals from the double inductive sensor for the radial component: (a) separate plots from assemblies I and II; (b) combined plots of both assemblies.
From Equation (8) the output signal of the double inductive sensor for the radial component is

\[ E(x) = k_v \frac{d[\bar{B}_{r0}(-c) + \bar{B}_{r1}(x+c)]}{dx} \]

\[ + k_v \frac{d[\bar{B}_{r0}(+c) + \bar{B}_{r1}(x-c)]}{dx} \]

\[ = k_v \left( \frac{d\bar{B}_{r0}(x+c)}{dx} + \frac{d\bar{B}_{r1}(x-c)}{dx} \right) \] \hspace{1cm} (13)

because

\[ \frac{d\bar{B}_{r0}(-c)}{dx} = \frac{d\bar{B}_{r0}(+c)}{dx} = 0 \]

Equation (13) shows that the initial level \( B_{i0} \) of the radial component \( B_i \) does not affect the output signal \( E \).

Samples of the electromotive forces \( E_I \) and \( E_{II} \) received from assemblies I and II respectively are shown in Figure 4a, while Figure 4b shows the output signal \( E \) from the whole sensor. For short defects the peaks of this signal occur at one side of the zero-level and their amplitude is almost twice as large as for one assembly.

The inductive sensor for the tangential component

The principle of the inductive sensor measuring the tangential component \( B_t \) of the magnetic flux density around the rope is shown in Figure 5. The cores of the inductive coils are placed between two ferromagnetic sleeves surrounding the rope.

In this design the magnetic flux \( \phi_c \) passing through all the cores is proportional to the average value \( \bar{B}_t \) of the tangential component measured at a distance \( R \) from the axis of the rope:

\[ \phi_c(x) = k_c \bar{B}_t(x) \] \hspace{1cm} (14)

where \( k_c \) is a coefficient depending on the design and material of the sleeves and cores.

The outputs of all the inductive coils of the sensor are connected in series and the output voltage of the sensor is

\[ E(x) = k \frac{d\bar{B}_t(x)}{dt} \] \hspace{1cm} (15)

where \( k \) is a new coefficient - the sensitivity of the sensor.

\[ \text{Fig. 5 The inductive sensor for the tangential component} \]

It was shown by Kalwa and Piekarski\textsuperscript{10} that the tangential component \( B_t \) consists of two parts - the initial level \( B_{i0} \) affected by the initial cross-section of the rope and the variations \( B_{it} \) caused by defects occurring in the rope:

\[ B_t(x) = B_{i0} + B_{it}(x) \] \hspace{1cm} (16)

Since

\[ \frac{dB_{i0}}{dx} = 0 \]

and

\[ \frac{d\bar{B}_{i0}(x)}{dx} = \frac{d\bar{B}_{i1}(x)}{dx} = \frac{d\bar{B}_{i1}(x)}{dx} \]

we have

\[ E(x) = k_v \frac{d\bar{B}_{i1}(x)}{dx} \] \hspace{1cm} (18)

Equation (18) indicates that the electromotive force \( E \) of the inductive sensor for the tangential component does not depend on the initial level \( B_{i0} \). Samples of the average tangential component \( B_t \) for various gaps of broken wires are shown in Figure 6a, while the output signal \( E \) is shown in Figure 6b. For short defects the spikes of the signal occur at both sides of the zero-level, while for long defects the signal also displays a zero-value at the middle of the defect.

The differential inductive sensor for the tangential component

Figure 7 shows the inductive sensor consisting of three sleeves forming two assemblies by sharing the centre sleeve. The inductive coils are placed between the centre sleeve and the clasp connecting the outer sleeves. Such a differential connection of assemblies I and II means that the magnetic flux passing through the cores of the inductive coils is

\[ \phi_c(x) = \phi_{cI}(x) - \phi_{cII}(x) \] \hspace{1cm} (19)

where \( x \) is the position of the defect along the 'x' axis, \( \phi_{cI} \) is the magnetic flux in assembly I and \( \phi_{cII} \) is the magnetic flux in assembly II.

Both assemblies are placed at a distance \( c \) from the symmetry plane of the magnetic head:

\[ \phi_{cI}(x) = k_{cI} \bar{B}_t(x+c) \]

\[ \phi_{cII}(x) = k_{cII} \bar{B}_t(x-c) \] \hspace{1cm} (20)

where \( k_{cI} \) and \( k_{cII} \) are coefficients depending on the design and material of the sleeves, cores and clasp for assemblies I and II respectively.

Assuming a symmetrical design of the sensor we have

\[ k_{cI} = k_{cII} = k_c \] \hspace{1cm} (21)

Since

\[ \bar{B}_t(x) = B_{i0} + B_{it}(x) \] \hspace{1cm} (22)

then

\[ \phi_{cI}(x) = k_c [B_{i0}(-c) + \bar{B}_{it}(x+c)] \]

\[ \phi_{cII}(x) = k_c [B_{i0}(+c) + \bar{B}_{it}(x-c)] \] \hspace{1cm} (23)

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Thus the resultant magnetic flux passing through the cores is

$$\phi_c = k_c \left[ (B_{10}(-c) + B_{11}(x+c)) - (B_{10}(+c) + B_{11}(x-c)) \right]$$

(24)

It was shown by Kalwa and Piekarski\textsuperscript{11} that the initial level $B_{10}$ of the tangential component maintains the same value at both sides of the magnetic head; therefore

$$B_{10}(-c) = B_{10}(+c)$$

(25)

Then the resultant magnetic flux is

$$\phi_c(x) = k_c \left[ B_{11}(x+c) - B_{11}(x-c) \right]$$

(26)

and its derivative with respect to time is

$$\frac{d\phi_c(x)}{dt} = k_c \frac{d \left[ B_{11}(x+c) - B_{11}(x-c) \right]}{dt}$$

(27)

Taking into account that

$$\frac{d \left[ B_{11}(x+c) - B_{11}(x-c) \right]}{dt} = \frac{d \left[ B_{11}(x+c) - B_{11}(x-c) \right]}{dx} \frac{dx}{dt}$$

(28)

where $r$ is the speed of the defect passing through the sensor, the output signal of the differential inductive sensor for the tangential component is

$$E(x) = k_v \frac{d \left[ B_{11}(x+c) - B_{11}(x-c) \right]}{dx}$$

(29)

where $k$ is a new coefficient - the sensitivity of the sensor.

Samples of the magnetic flux $\phi_c$ passing through the cores are shown in Figure 8a, while the corresponding output signals $E$ are shown in Figure 8b. For short defects the spikes of the output signal occur at one side of the zero-level.
**Discussion**

The four inductive sensors provide different signals depending on the profile of the magnetic concentrators.

The radial component sensor (Figure 1) has one pair of rings and the peaks of its signal occur at the centre of the zero-level for short defects. For a long defect (for example, a missing wire) the signal indicates the beginning and the end of such a defect.

The double radial component sensor (Figure 3) has a more complicated structure but provides a signal with larger amplitude, although the character of the signal remains the same as for the single radial component sensor.

The tangential component sensor (Figure 5) has sleeves instead of rings as concentrators, which allows closer positioning of the inductive coil to the rope and reduces the effect of a very high initial level $B_{in}$. However, the spikes of its signal occur at both sides of the zero-level for short defects, which is not as convenient for further processing as spikes at one side of the zero-level.

The differential sensor for the tangential component (Figure 7) has a more complicated structure but provides a much stronger signal and also reduces the effect of the initial level $B_{in}$.

Common to all of these sensors is that they provide signals maintaining zero-level outside the defect and also at the central part of a long defect. The amplitude of their signal depends on the intensity of variations of the radial and tangential components along the axis of the rope (i.e., on the amplitude and width of $B_r(x)$ and $B_t(x)$ plots).

It was found by Kalwa and Piekarski\[1\] that the amplitude of $B_r$ and $B_t$ depends linearly on the cross-section of the damaged wire and non-linearly on the gap size $s$, while the width of $B_r$ and $B_t$ is affected only by the gap size $s$. These relationships can be used in reverse to estimate the diameter of the broken wire and the gap size $s$ when the amplitude and width of the signal from the sensor are known.

It was also shown by Kalwa and Piekarski\[1] that for multiple defects variations of the radial and tangential components decrease their amplitude. In such cases the signal from any inductive sensor will not allow the quantitative determination of the weakness of the rope, although multiple spikes of the signal will indicate the general character of the wear of the rope\[2\].

It is also important that inductive sensors are simpler and easier to operate than Hall-effect sensors. They do not require a supply of energy for their operation and the output signal does not have to be zeroed. Thus the
Conclusions

1. By adopting the magnetic concentrators used for Hall-effect sensors, inductive sensors can be built to provide different output signals to those from Hall-effect sensors.
2. The character of the output signal and the sensitivity depend on the profile of the magnetic concentrators in the sensor.
3. Although the application of inductive sensors is limited to the initial and middle stages of the deterioration of the rope, they can be satisfactory and competitive with Hall-effect sensors for periodic checks of many wire ropes.

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