Velocity measurement method of moving object with a magnetic field source based on the measurement of the difference signal of two induction sensors

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Abstract. The article describes a new method for measuring the velocity of movement of an object with a magnetic field source. A moving plasma piston in a channel of a magnetoplasma accelerator, which is essentially a moving conductor with current, is considered as an example of such an object. The method is based on the measurement of the difference signal of two induction sensors. The advantage of the method is the presence of a linear dependence between the primary measuring signal (difference signal) and the final informative parameter (the value of the velocity of movement of the conductor with current). The task of simplifying the velocity measurement is solved at the expense of this advantage.

1. Introduction
The task of measuring the position and velocity of moving objects with a magnetic field source arises in many technical applications. Examples are devices for measuring displacements using magnetometric sensors (magnetoresistors or Hall sensors) and permanent magnets [1-4].

The article discusses another example: the task of measuring the velocity of a plasma piston in a magnetoplasma accelerator [5-12]. The plasma piston is a moving conductor with a current, that is, a moving source of a magnetic field. It moves linearly along two conductive rails, and the current source is a special high-voltage storage device. A high voltage source, rail guides and a plasma piston form a closed electrical circuit.

The article proposes a new velocity measurement method for moving object with a magnetic field source on the example of the velocity measurement of moving conductor with current.

2. Methodology section of this paper
The output signal \( u \) of a magnetometric sensor, perturbed by the magnetic field of a moving conductor with current \( I \), in general form can be represented as follows.

\[
 u(x(t)) = K f(x(t)).
\]

Here \( K \) – coefficient taking into account sensor parameters and physical constants; \( f(x(t)) \) – multiplicative component of the sensor signal, which is a complex function of the coordinate \( x(t) \) of the position of the conductor on the trajectory of its movement; \( t \) – time.
Thus, the functions of the output signals of a pair of sensors installed along the path of a conductor with a current when it is located between the sensors can be described using (1) by the following formulas

\[
u_1[x(t)] = KI f[x(t) + L/2] \quad (2)\\
\]

\[
u_1[x(t)] = KI f[x(t) + L/2] \quad (3)
\]

where \(L\) – distance between the sensors and the middle of this distance is taken as the zero point of the \(x\) coordinates.

A group of methods for measuring the velocity of moving conductor with a current, based on measuring the signals of two magnetometric sensors and a special secondary conversion of these signals, which allows to allocate the final informative parameter (velocity) is described in [5,10-12].

The specific type of secondary transformation is determined by a separate method.

For example, this is the method of measuring velocity using differential-ratiometric secondary conversion of the signals [5, 10]. According to this method, the measurement is made on the section of the trajectory between two identical magnetometric sensors with a bell-shaped transfer characteristic. Such primary transducers can be Hall sensors or induction sensors with an integrator.

Previously, prior to the measurement, the value of the special scaling coefficient \(X_c\) is assumed. It should be numerically equal to the value of the displacement of the monitored conductor, corresponding to the change in the output signal of each sensor by \(e\) times. During the movement of a conductor with a current, the primary signals \(u_1(t), u_2(t)\) of two sensors are measured continuously, the secondary transformation is performed by the formula

\[
F(t) = (u_1(t) - u_2(t))/(u_1(t) + u_2(t))
\]

and the velocity \(v(t)\) is determined by the formula

\[
v(t) = X_c \frac{dF}{dt} / (1 - F^2).
\]

The considered method has low noise immunity in the presence of strong impulse noise. This is due to the presence of a time differentiation operation of the function of the secondary transform \(F\), which leads to “underlining” the noise present at the input of the measuring device.

As an example of a method for measuring the velocity of moving conductor with a current without applying a differentiation operation, one can use a method using a secondary transformation based on the geometric averaging of the signals of two induction sensors [12]. Moreover, taking into account the specificity of the type of primary converters, relations (2) and (3) can be specified as follows

\[
u_1[x(t)] = NS_v v(t) \frac{\mu_0}{4\pi} I f[x(t) + L/2] \quad (4)\\
\]

\[
u_2[x(t)] = NS_v v(t) \frac{\mu_0}{4\pi} I f[x(t) + L/2] \quad (5)
\]

where \(N, S_v\) – the number of turns and sectional area of the induction sensor coil, respectively; \(v\) – the velocity of the moving conductor with current; \(\mu_0 = 4\pi \cdot 10^{-7} \text{ [H/m]}\) – magnetic constant.

The velocity measurement is made on the section of the trajectory between two identical induction sensors in accordance with the described method. Similarly to the previous method, the value of the special scaling coefficient \(X_c\) is preliminarily assumed, and in the process of the moving conductor, the signals \(u_1(t), u_2(t)\) of two sensors are measured continuously. An additional measurement of the current \(I\) flowing in the monitored conductor is assumed. The current can be measured on a stationary portion of an electrical circuit in which a moving conductor is connected. The geometric averaging of the values of the signals of two induction sensors is assumed as a secondary transformation, which is here the final operation of determining the velocity.
\[ v(t) = K \frac{\sqrt{u_1(t) \cdot u_2(t)}}{I} \]

where \( K = \frac{X_c^2 - 4\pi}{\mu_0 NS_s} \) – constant coefficient.

The disadvantage of this method is that in the measuring device, that implements this method, square root extraction block is required. This block is relatively complex in the case of its implementation in the hardware analog version, which causes additional instrumental error. The square root extraction unit can be implemented virtually as a separate software module in the case of using digital processing of primary signals. But in this case, the square root calculation is a more complex computational operation, which causes long time delays, compared to linear operations. Thus, the need to extract the square root complicates the velocity measurement procedure regardless of the version of the measuring device.

Consider a new method for measuring the velocity of the moving conductor with a current, the crucial task of simplifying measurement. The advantage of the proposed method is that it contains a linear relationship between the primary measuring signal and the final informative parameter (the value of the velocity of the conductor with current), which solves the problem of simplifying the velocity measurement.

According to the new method, similarly to the previous one, the velocity measurement is made on the section of the trajectory between two identical induction sensors, the signals \( u_1(t), u_2(t) \) of said sensors are measured continuously and it is assumed that the current \( I \), flowing in the controlled conductor is measured. A distinctive feature of the method is that the difference signal \( u_d(t) \) of two sensors generated by the field of a moving conductor is continuously measured, and its velocity \( v(t) \) is determined by the formula

\[ v(t) = K \frac{u_d(t)}{I} \]  \hspace{1cm} (6)

where \( K = \frac{1}{C} \frac{4\pi}{\mu_0 NS_s} \); \( C \) – constant coefficient, determined by the results of a preliminary physical experiment or computer modeling.

The difference signal \( u_d[x(t)] \) of two induction sensors reacting to a moving conductor with current, taking into account (4) and (5), is determined by the formula

\[ u_d[x(t)] = u_1[x(t)] - u_2[x(t)] = NS_s v(t) \frac{\mu_0 I}{4\pi} \{ f[x(t)+L/2] - f[x(t)-L/2] \}. \]  \hspace{1cm} (7)

As shown below, it is possible to distinguish a section on the function of the difference signal, which can be characterized as fairly constant, that is, not changing with a change in the value of \( x \). This is due to the fact that the characters of changes in functions \( f[x(t)+L/2] \) and \( f[x(t)-L/2] \) on the right-hand side of (7) in the said area are quite close to each other. Consequently, the component \( \{ f[x(t)+L/2] - f[x(t)-L/2] \} \) in (7) can be with a sufficient degree of accuracy replaced by some constant coefficient \( C \), having the dimension \([1/m^2]\). Therefore, formula (7) is changed as follows

\[ u_d[x(t)] = NS_s v(t) \frac{\mu_0 I}{4\pi} C. \]  \hspace{1cm} (8)

Thus, from (8) it follows that the velocity \( v(t) \) of the moving conductor with current can be determined by continuously measuring the difference signal \( u_d(t) \) of two identical induction sensors created by a field of a conductor with a current that moves in the section of the trajectory between
these sensors and when measuring the current $I$, flowing in the conductor. The velocity is determined by the formula

$$v(t) = \frac{1}{C} \frac{4\pi}{\mu_0 N_S} \frac{u_d(t)}{I}. \quad (9)$$

Formula (6) is the final formula for determining the velocity $v(t)$. It can be obtained by denoting by $K$ the constant coefficient $\frac{1}{C} \frac{4\pi}{\mu_0 N_S}$ in (9).

Thus, a linear relationship between the primary measuring signal $u_d(t)$ and the final informative parameter (velocity value $v(t)$ of the movement of a conductor with current) exists in the new method. This follows from (6), due to which the task of simplifying the measurement is solved.

3. Results and Discussion
A computational experiment was conducted to investigate a new method for measuring the velocity of the moving current-carrying conductor.

Figures 1 and 2 show the results of computer simulation of the signals $u_1[x(t)]$, $u_2[x(t)]$ of two sensors reacting to a moving conductor with current, as well as their difference signal $u_d[x(t)]$.

Monitored object (conductor with current - source of magnetic field), trajectory of the conductor and two induction sensors S1 and S2 are schematically shown in area (a) of figure 1. The graphs of the signals of two induction sensors and their difference signal as functions, depending on the $x$-coordinate of the conductor position with current: $u_1(x)$, $u_2(x)$ and $u_d(x)$ are represented in areas (b) and (c) of figure 1.

![Figure 1](image)

Figure 1. The signals of the first and second induction sensors, reacting to a moving conductor with current and their difference signal (the function, depending on the position coordinates of the conductor).
$u_2(x)$ in the respective areas (highlighted with a thick line in figure 1-b) are quite close to each other. Consequently, the nature of the dependence of the difference signal of two induction sensors on the velocity of the moving conductor with a current in a certain part of the trajectory (highlighted in bold line in figure 1-a) is close enough to proportional and in this area it is possible to measure the velocity using formula (6). Thus, the selected area is a measuring area. The figure 2 presents the graph of the differential signal of two inductive sensors as a function of time: $u_d(t)$. The same graph shows the function $v(t)$ of the velocity of the moving monitored conductor with current. The values of the differential signal are reduced to the values of the velocity using the proportionality coefficient so that in the selected measurement area the function of the difference signal of the two sensors repeats the area of the velocity function of the moving conductor with current with a sufficient degree of accuracy. This corresponds to the velocity measurement formula represented by the formula (6).

![Figure 2](image_url)

**Figure 2.** The velocity of the moving conductor with current and the difference signal of two inductive sensors, reduced to velocity values as a function of time.

4. Conclusion

Thus, the results of computer modeling confirm the validity of the new velocity measurement method of moving conductor with current. The presence of a linear relationship between the primary measurement parameter (difference signal of two inductive sensors) and the final informative parameter (velocity of moving conductor with current) simplifies the measurement of velocity.

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