

Fluxgate Sensors for Onboard Weighing Systems of Heavy-Duty Dump Trucks



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ABSTRACT

The article reviews the results of the authors' research on the possibility of using the magnetic field strength generated by DC traction motors as a useful signal carrying information about weight of cargo transported by a mining dump truck.

The objective of the research was to find a way to determine weight of cargo carried by a mining dump truck. In contrast to the existing onboard weighing systems, it becomes possible to create a compact autonomous device that does not require integration of sensors into the body structure and electrical circuits of the truck.

Problems of increasing the efficiency of measuring devices based on fluxgate converters are considered with the view of using them as onboard systems for estimating cargo weight. The sensitivity of the fluxgate sensor can be increased by increasing both the amplitude and the effective value of the voltage applied to its excitation winding. The proposed original circuit for feeding the fluxgate sensor's excitation winding from a modulated signal generator made on logical elements allows increasing the voltage supplied to the fluxgate sensor's excitation winding without increasing the supply voltage, and by increasing voltage surges at the fronts of rectangular modulated high-frequency pulses, as well

as due to resonant phenomena. The use of such a generator excludes the influence of the fluxgate sensor's excitation winding on the generator frequency, since the frequency of modulating signals becomes the operating frequency of the fluxgate sensor, and it remains unchanged. The increased sensitivity makes it possible to install the sensor in any convenient place in the dump truck cab, and not in the immediate vicinity of traction motors.

Evaluation of cargo weight is carried out during movement of the dump truck along the control section of the road. The readings are taken from an ammeter (milliammeter), the scale of which is pre-calibrated in mass units. Measurements of mass should be carried out under the same modes of dump truck movement and with the same location of the fluxgate sensor as when calibrating the scale of the measuring device. The control section of the route on which the measurements are carried out must be the same or similar to the one on which the measuring device was calibrated.

The proposed device is distinguished by ease of use, is characterised by low energy consumption, is compact, does not contain expensive elements and does not require careful maintenance.

Keywords: transport, onboard weighing systems, load mass, mining dump truck, DC traction motors, magnetic field strength, fluxgate sensor.

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INTRODUCTION

Determining weight of the cargo of heavy-duty vehicles used in open-cut mining enterprises is traditionally the most significant task, the solution of which can be carried out in different ways.

A rough estimate of the degree of filling the body with rock mass, which takes place at about 95 % of enterprises, provides that the excavator driver respects the loading specifications. The loading specifications for each type of vehicle determine the order of placing the cargo and uniformity of its distribution in the body, as well as the necessary parameters of the load «heap» [1].

However, compliance with the requirements of the loading specifications is ineffective for assessing the mass of the cargo due to its inaccuracy. When controlled according to the loading specifications, the «underload–overload» range is $\pm 25\%$ and more [1, p. 132].

For a more accurate measurement, stationary truck scales are used. Such scales are reliable, have a large margin of safety, however, they require that the entire truck is situated on the platform, which leads to a loss of time. Besides, the location of the loading site can change quite often. There are also mobile scales, but it is not always convenient to use them [3, p. 147].

The most effective way is to automatically control loading using built-in onboard systems. Onboard weighing systems (OWS) use special sensors such as pressure sensors and strain gauges [4].

Most often, onboard systems used on mining dump trucks determine the mass of the cargo by the steady-state values of gas pressure in suspension cylinders. These systems are quite easy to install, but they are only applicable to vehicles with air suspension on all axles.

The disadvantage of such systems is dependence of measurement results on viscosity of the oil in the hydraulic system, which changes with ambient temperature fluctuations, which, in turn, affects the pressure in the system. This introduces errors in readings of the onboard weighing system based on pressure sensors. The error is also explained by the presence of significant dry friction forces in suspension cylinders. Some manufacturers solve the problem of inaccuracy by introducing the calculation of corrections into the electronic OWS software [2].

Unlike pressure sensors systems, strain gauge systems provide higher accuracy. Load cells in

onboard systems are installed between the frame and the car body and can be used on any vehicles with a tipper body and with any type of suspension. Onboard systems based on strain gauges are reliable and of low-maintenance type. However, such systems require replacement of standard body attachment units with units with strain gauges, which can be done by qualified specialists only in workshop conditions.

Since 2000, onboard weighing systems have been developed by various companies, e.g., by BELAZ holding company (Zhodino, Belarus), Vist Group (Moscow, Russia). The systems are built based on an onboard controller that collects and processes many performance indicators of a dump truck [7]. Such systems provide load normalization within $\pm 8\%$ relative to the rated carrying capacity [5].

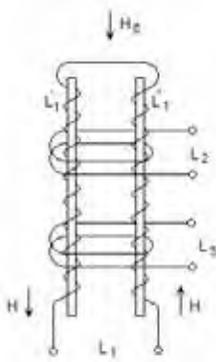
The *objective* of the research carried out by the authors was to find a way to estimate the mass of the cargo of a mining dump truck, which simplifies measurements, but does not require careful integration of sensors into structural elements of heavy-load vehicles. Such a method might increase the efficiency of the technological process for assessing weight of the cargo, significantly reduce energy, time, and financial costs, without the use of complex and expensive engineering equipment and without involvement of qualified personnel.

RESULTS

Proposed Solution

The proposed solution is as follows: the magnitude of the magnetic field strength generated by DC traction motors of a mining dump truck is measured. E.g., BelAZ-75121 dump truck uses DK-722E traction motors. These are DC brushed motors located in wheel hubs. As it is well known, the amount of current consumed by a traction motor is determined by the amount of load on its shaft, which, in turn, depends on the mass of the transported cargo and the conditions of movement: speed, features of this section of the route (hill, slope, quality of the roadbed, etc.).

The motor's current produces a constant, slowly changing magnetic field, the strength of which can be measured. The use of the strength of the magnetic field generated by the motor, instead of the motor current, as of a diagnostic parameter allows the measurement to be carried out in a non-contact way, without interfering with electrical circuits [10].



Pic. 1. Structure of a fluxgate sensor: H – fluxgate sensor's excitation field, H_0 – measured magnetic field (compiled by the authors).

The proposed solution uses the relationship between the intensity of the magnetic field generated by the DC motor and the load on the motor shaft, which determines the mass of the dump truck.

To measure the magnetic field strength, various sensors can be used, e.g., fluxgate sensors, which convert the magnitude of the magnetic field strength into the magnitude of the current. The fluxgate method of measuring the strength is quite simple, well studied and allows you to achieve the required accuracy [8; 9; 15; 16].

The motors of heavy-duty dump trucks create a sufficiently strong magnetic field, so there is no need to install a fluxgate sensor in the immediate vicinity of the motor or of power supply circuits of the motor. An ammeter (milliammeter) is used as an indication device, the scale of which is calibrated in mass units.

In practice, the location where fluxgate sensor is mounted does not matter. It is only important that it is the same both when calibrating the milliammeter scale and when measuring.

The scale is calibrated in the following sequence:

1. A route section with certain parameters is selected, which is declared a control one. For example, a plot with a constant slope and the same quality of road surface. It is advisable to choose a section with such parameters that are most typical for the proposed route of the truck.

2. The truck without cargo moves along the control section of the road in a certain mode (for example, at a constant speed). The travel time should be sufficient to take the milliammeter reading, which is further taken as zero load weight.

3. The truck moves in the same mode along the same section (or similar section) of the road

with a load, the mass of which is known. The milliammeter reading will correspond to the load weight.

4. The actions stipulated in paragraph 3, for a more accurate calibration of the scale and elimination of errors, can be repeated with a different load weight. In this case, the scale of the calibrated milliammeter turns out to be almost linear.

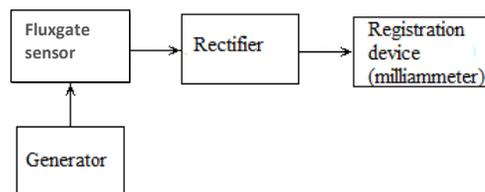
To measure mass, it is necessary to:

1. Provide a control section of the road, or a section similar to the control one in its parameters, where calibration was carried out and to which the scale of the measuring device (milliammeter) corresponds.

2. Ensure travelling of a dump truck for at least 5–10 seconds along the control section with the same constant speed at which the calibration of the measuring device scale was performed.

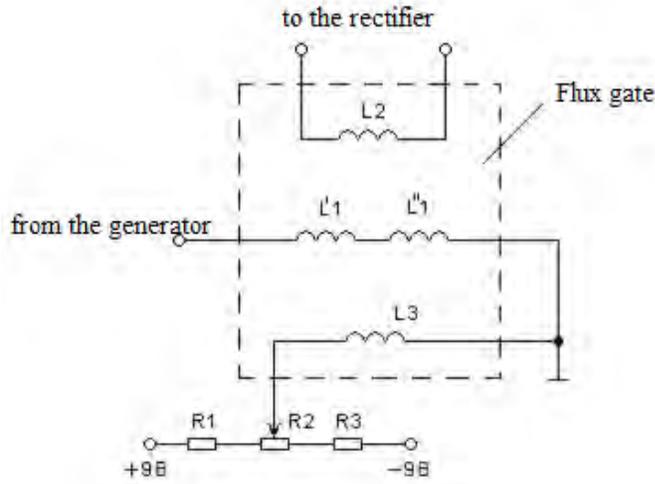
3. Make non-contact measurements using a measuring device based on a fluxgate sensor and take readings from the measuring device, the scale of which is pre-calibrated in mass units.

When measuring the weight of the cargo transported by vehicles of the same model, there is no need to calibrate the scale of the measuring device for each vehicle separately. It is enough to provide only the same place of mounting of the sensitive element (fluxgate sensor).

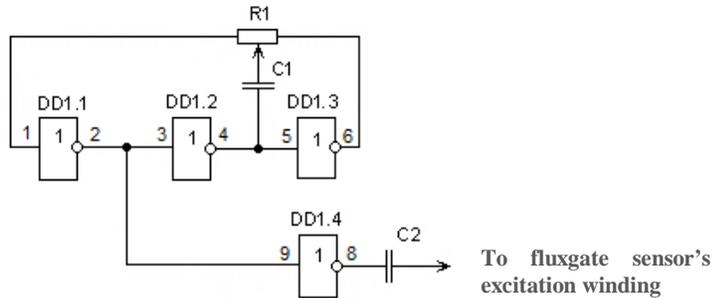


Pic. 2. Block diagram of the measuring device (compiled by the authors).





Pic. 3. Scheme of switching on the fluxgate sensor's windings (compiled by the authors).



Pic. 4. Generator of rectangular pulses for powering the excitation winding of the fluxgate sensor (compiled by the authors).

Its structure is shown in Pic. 1: the measuring winding L_2 is on top of two cores with windings L'_1 and L''_1 .

To compensate for the influence of extraneous sources, an additional third winding L_3 is provided, located on top of the main windings (not shown in Pic. 1).

The block diagram of the measuring device through which the method is implemented is shown in Pic. 2.

The block diagram includes:

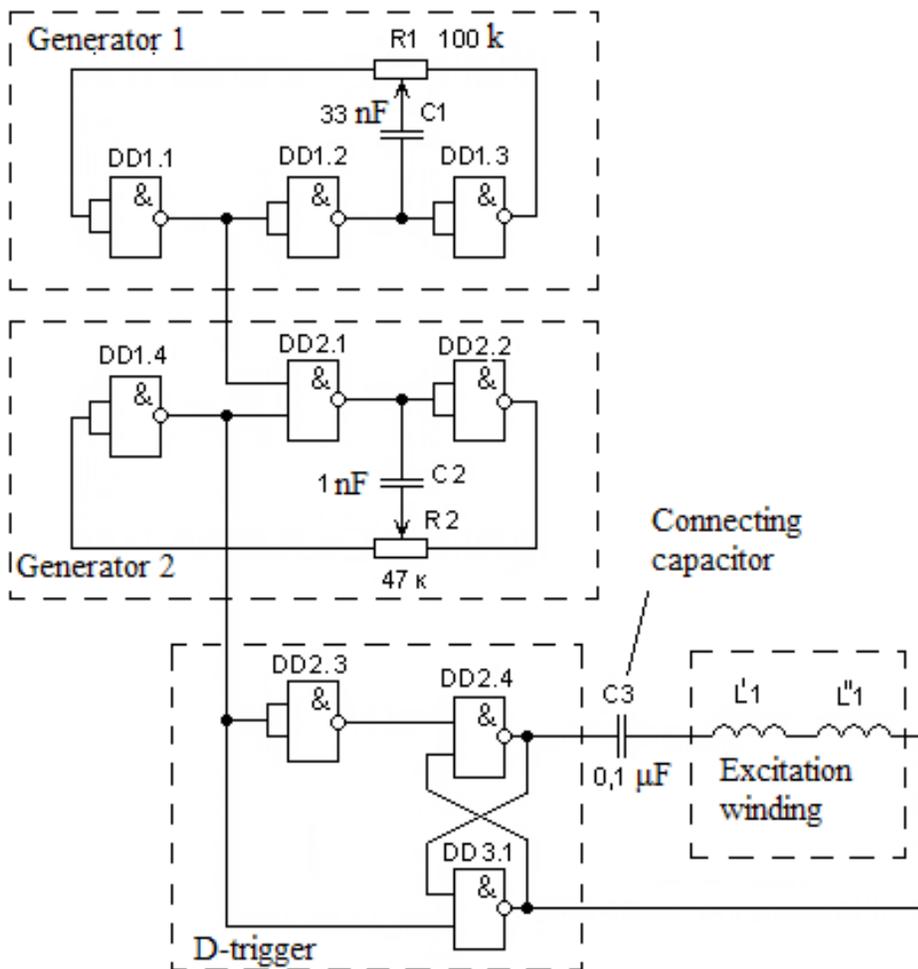
- A pulse generator that forms rectangular pulses supplied to the excitation winding L_1 of the fluxgate sensor.
- Fluxgate sensor including three windings.
- Rectifier.
- Registration device: milliammeter.

The scheme for switching on the fluxgate sensor's windings is shown in Pic. 3.

Compensation of extraneous fields is carried out with the dump truck motor turned off by a variable resistor R_2 by setting the current value to zero, measured by a milliammeter. The values of the resistors R_1 and R_3 are selected depending on the milliammeter used and the voltage value.

Experiments have shown (and this is in good agreement with the data of research literature sources) that the efficiency of fluxgate converters is largely determined by the amplitude, frequency, and shape of the excitation signal; in this case, a rectangular waveform gives a better result in comparison with a sinusoidal or triangular waveform [14; 15].

To power the fluxgate sensor's excitation winding, a simple rectangular pulse generator can be used, the diagram of which is shown in Pic. 4.



Pic. 5. Modified circuit for feeding the excitation winding of the fluxgate sensor (compiled by the authors).

The circuit contains four logical NOT elements (K561 LN2 microcircuit), powered by a 9-volt source. The generator itself comprises first three NOT components. The fourth NOT component (DD1.4) is useful for eliminating the influence of the fluxgate sensor's excitation winding on the generator operation. Resistor R_1 and capacitance C_1 are frequency setting elements. The resistor R_1 controls the generator frequency. For the fluxgate sensor described above, a frequency of 2 kHz is used. The circuit is simple, has low power consumption, allows a compact and economical implementation, and makes it possible to reduce the size of the measuring device.

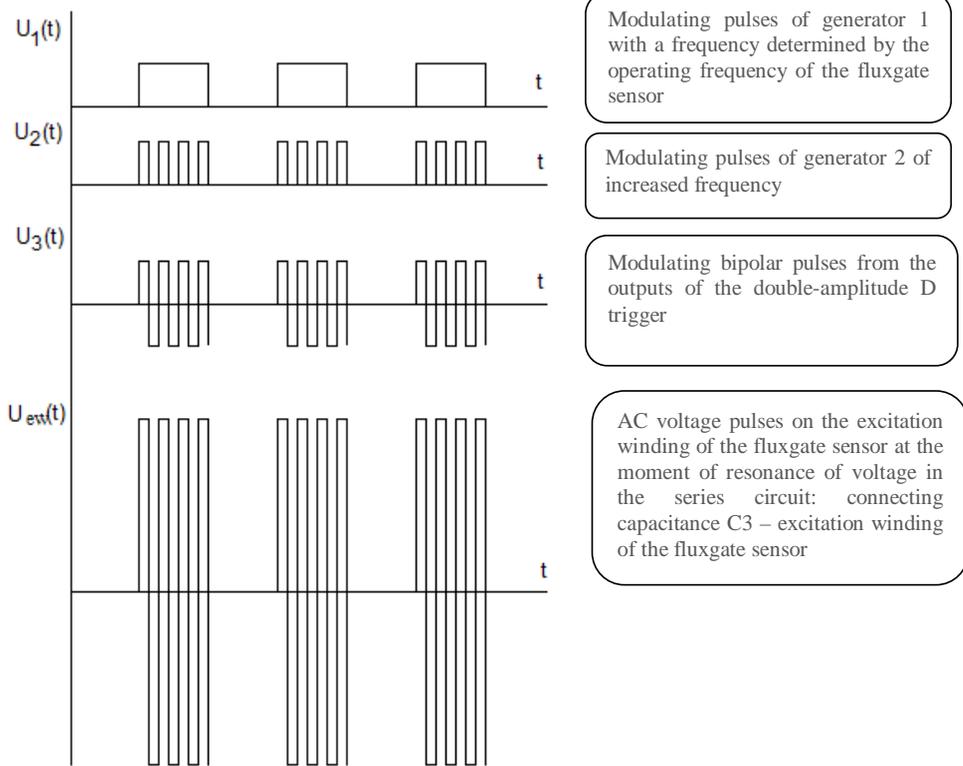
The circuit uses capacitive coupling of the generator with the fluxgate sensor's excitation winding (capacitance C_2 in Pic. 4). This makes it possible to exclude the direct component of the

generator signal and, consequently, to reduce the excitation winding's current and the power consumption of the measuring device [15].

The use of a circuit based on NOT logic components (Pic. 4) as a generator makes the measuring device simple, reliable, and compact.

Studies have shown that sensitivity of the fluxgate sensor can be increased by increasing the voltage (amplitude and effective value) supplied to the excitation winding from the generator. For this purpose, it is possible to use the resonance phenomena arising in the resulting series circuit: the capacitor C_2 – excitation winding of the fluxgate sensor. By selecting the value of the capacitance of the connecting capacitor and the frequency of the generator, it is possible to achieve a sharp increase in the sensitivity of the fluxgate sensor. This is due to an additional increase in the voltage across the





Pic. 6. Timing diagrams of voltages (compiled by the authors).

excitation winding due to the resulting voltage resonance.

Studies have also shown that at an increased frequency of fluxgate sensor's feeding, the voltage on the excitation winding increases due to voltage surges arising on the positive and negative edges of rectangular pulses when the generator is operating to produce inductive load. But for a significant increase in voltage (and for a consecutive increase in the fluxgate sensor's sensitivity), a power supply frequency of the order of 100 kHz or more is required. However, the specified frequency of the fluxgate sensor, at which its operation is most effective, is lower than these values.

Thus, to increase the sensitivity of the fluxgate sensor, it is required to increase the frequency of the voltage supplied to the excitation winding; then, at this increased frequency to achieve voltage resonance, but at the same time to ensure the standard specified operating frequency of powering the excitation winding of the fluxgate sensor.

To increase the frequency of the fluxgate sensor's power supply voltage and maintain the required rated frequency, it is proposed to use two generators to power the fluxgate sensor. The first generator generates modulating rectangular pulses that power the excitation winding. The repetition rate of these pulses is determined by the operating frequency of the fluxgate sensor. The first generator controls operation of the second generator, which generates modulated square-wave pulses of increased frequency. At this frequency (at a certain value of the capacitance of the connecting capacitor), voltage resonance appears, and the effect of voltage surges on the amplitude and effective value of the voltage of the pulse generated by the first generator becomes noticeable. In this case, high-frequency pulses of the second generator occur only at the moments of the presence of pulses of the first generator.

The modified circuit for powering the excitation winding takes the form shown in Pic. 5.

Generator 1 and generator 2 are of the same type, both are made on three 2AND-NOT elements of the 564LA7 microcircuit. The amplitudes of the pulses that they generate are determined by the supply voltage of the generators. Elements R, C of generators set the required frequencies. Variable resistance R1 of generator 1 provides tuning of modulating pulses to the operating frequency specified in the documentation for the fluxgate sensor. Variable resistance R2 of generator 2 sets a high frequency of modulated pulses, which provides resonance of the voltage across the excitation winding. The value of the capacitance of the connecting capacitor C3, as a rule, does not exceed 0,1 μ F.

Pic. 6 shows voltage timing diagrams that explain the purpose and operation of individual parts of the circuit shown in Pic. 5.

At frequencies of 100–200 kHz of modulated pulses, the influence of voltage surges (not shown in Pic. 6), which occur during operation producing an inductive load, on the magnitude of both the amplitude and the effective value of the voltage across the excitation winding of the fluxgate sensor, is clearly noticeable.

The duration of surges is short and amounts to a few microseconds, but their amplitude can be several times higher than the voltage in a rectangular pulse. And at an increased repetition rate of modulated pulses, their duration becomes commensurate with the duration of the pulses themselves, and the effect of surges on the voltage of the excitation winding increases significantly.

A further increase in frequency above 200 kHz is undesirable since it leads to a noticeable increase in power consumption.

In the circuit shown in Pic. 5, the voltage from the output of generator 2 is applied to the excitation winding through D-trigger. This makes it possible to obtain a bipolar voltage waveform with double the voltage swing, which also increases the sensitivity of the measuring device. In addition, when using a trigger, the influence of the fluxgate sensor's excitation winding on the generator operation is reduced.

Such a modification of the generator circuit makes it possible to significantly increase the sensitivity of the fluxgate converter without increasing the voltage of the power source.

Experimental Verification

During the experiments, the tested fluxgate sensor had the following winding data:

- Diameter of the field winding wire was 0,3 mm, the number of turns of each half of the excitation winding was 200. There was single layer winding, turn to turn. It connects to a pulse generator.

- Measuring winding: number of turns was 2000, wire diameter was 0,1 mm. The winding was multilayer one, turn to turn. The measuring winding is connected through a rectifier to a recording device, which is a DC ammeter (milliammeter).

- The diameter of the wire of the additional winding was 0,1 mm, the number of turns was 500.

To protect the fluxgate sensor against extraneous external influences, a protective casing was used, which was a brass tube [14].

Experimental verification was carried out by the authors at the Ekibastuz coal basin (Severny mine) on BelAZ-75121 heavy-duty dump trucks using DK-722E traction motors. The experiment showed almost complete coincidence of the value of the weight of the cargo, obtained with the help of a fluxgate sensor measuring device, with the value measured on a truck scale. It was also experimentally established that the readings of the measuring device do not depend on unevenness of the roadway. In addition, strict compliance of the measuring section of the road with the section on which the calibration of the measuring device was performed is not required. The main thing is to provide a similar slope of the track, as well as the same speed without sudden jerks and braking.

TECHNICAL RESULT AND CONCLUSIONS

The proposed non-contact method for measuring the load mass eliminates the need to embed sensors into structural elements and electrical circuits of a vehicle, does not require complex engineering equipment, and reduces time and costs of measurements, while ensuring sufficient accuracy.

A measuring device with a fluxgate sensor and a milliammeter can be installed almost anywhere in the truck, which provides convenient recording of measurement results.

The proposed method is easy to use. The device that implements the method is characterized by low energy consumption, it is compact, does not contain expensive elements and does not require careful maintenance. Preparing the device for operation consists in calibrating the scale of the measuring device (milliammeter) in mass units.



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