Schematic modeling of functional units of a magnetoelectric current sensor

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Abstract. The article is devoted to circuit simulation of functional units of a magnetoelectric current sensor. The magnetoelectric current sensor is designed to measure the current in electrical circuits of direct or alternating current in electrical engineering. The advantages of the developed magnetoelectric current sensors over existing analogs are higher sensitivity, lower power consumption, wide dynamic range of the output voltage, and better linearity of the output characteristics. In the course of the simulation, a model of the OA MCP6024-E/ST microcircuit from Microchip Technology Inc. was used, which is used as a signal amplifier for a magnetoelectric sensing element in a current sensor. Simulation of the signal generation unit, peak detector and linear amplifier was carried out. Circuitry solutions were proposed to improve the parameters of existing current sensors. Solutions have been found to ensure the temperature stability of the sensor. The developed magnetoelectric current sensors can be manufactured using integral technology and become a significant competitor to the traditional Hall effect sensors.

1. Introduction

Magnetoelectric (ME) current sensor is designed to measure current in electrical circuits of direct or alternating electric current in electrical engineering. ME current sensor (CS) can be used in measuring equipment, power networks and control systems, safeguarding and security systems; metal detectors; automotive industry; railway transport; wireless electricity metering systems; space technology and robotics for measuring both DC and AC current.

The closest analogs of the solutions on the market are sensors based on the Hall effect [1–3]. The general advantage of the developed ME sensors over the existing current sensors is their higher sensitivity. In the case of Hall effect sensors, the advantage is the lower power consumption. The difference from magnetoresistive sensors is low power consumption, a wider dynamic range of the output voltage. The difference from current transformers is the better linearity of the output characteristic. Current sensors based on the ME effect have significantly better performance compared to current sensors based on the Hall effect. A non-contact type of ME current sensor also eliminates the disadvantage of a contact type CS: the need to include the sensor directly in the open circuit. This solution is universal and allows integrating ME sensor into existing control systems.

It is necessary to apply constructive and functional solutions that meet modern requirements to obtain optimal results and a competitive ME effect current sensor. The use of new composite ME materials [4–5] in CS has become the most urgent solution. ME current sensor includes a voltage stabilizer, a generator, a detection system, an operational amplifier, and a peak detector [6]. In addition, an important part of the sensor is the electronic signal processing circuit. The detection system is the main part of the
ME current sensor and consists of an ME structure and a bias coil. Modification of the above functional units of the device will optimize the design and circuitry solutions of the sensor.

The purpose of the article is to consider a number of circuit solutions based on an operational amplifier to improve the parameters of the ME CS.

2. Simulation of the amplification circuit

An operational amplifier (OA) is determined by a number of basic characteristics that determine its operating parameters. Understanding the value of this or that parameter allows selecting the required type of OA for each target application and thereby ensure its operability and maintain the required parameters in an acceptable mode.

When developing a device based on modern OA, it is necessary to pay attention to the fact that the parameters of the OA in specific switching circuits can differ significantly from the intrinsic parameters of the OA considered below due to the strong influence on the parameters of the feedback circuits.

In the course of the simulation, a model of the OA MCP6024-E/ST chip from Microchip Technology Inc. was used, which is used as a signal amplifier from a magnetoelectric sensing element. This OA has low noise, low input current, and rail-to-rail input/output, which means that this OA can have input and/or output signals up to supply voltages. Low current consumption was also the main principle for choosing this element.

An amplifier circuit was built on an OA MCP602 series to evaluate the operating parameters of the amplification device (figure 1).

![Figure 1. Non-inverting amplifier circuit based on OA MCP602 series.](image)

In this circuit, resistor \( R_1 \) is installed to compensate for the bias currents. Resistor \( R_2 \) provides the piezoelectric discharge of the magnetoelectric structure. The feedback resistor \( R_4 = 90 \, \text{k}\Omega \) and the resistor \( R_3 = 10 \, \text{k}\Omega \) creates an amplification \( K_u = 10 \). This value is selected based on the values of the signal coming from the magnetically sensitive element, which is in the range from 0 to 500 mV. Resistor \( R_5 \) simulates a load.

A feature of the circuit on the OA MCP602 is a unipolar power supply, which means that only the positive half-wave is amplified and the negative half-wave is not passed through.

A model of the amplitude characteristics of the input and output voltage of the circuit was obtained, based on the constructed circuit model, to determine the real value of the gain of the circuit \( K_u \).
Figure 2. The graph of the input voltage versus time and the output signal versus time: the input voltage versus time graphs are shown in blue; the graphs of the output voltage versus time are shown in red.

Figure 2 shows two graphs of the dependence of the input and output voltage of the circuit on time. Based on the simulation, the gain of the circuit with a theoretical calculated value of $K_{\text{calc}} = 10$ and an input voltage of 100 mV was $K_{\text{mod}} \approx 10$ with an output voltage of 1.005V. A slight change in the value may be due to the fact that the simulation uses a real model of a non-ideal operational amplifier, where $I_{\text{in}} \neq 0$.

Next, the change in the amplitude of the signal source $V_s$ was set from 50 mV to 500 mV with a step of 50 mV. The lower and upper half-wave of the sinusoidal signal begins to be limited at different values of the amplitude of the input voltage. Results are shown in figure 3.

Figure 3. The graph of the dependence of the input and output voltage on time in the range of input signal amplitudes from 50 mV to 500 mV; blue color shows graphs of input voltage versus time; the graphs of the output voltage versus time are shown in red.
The threshold voltage to which the amplification circuit on the OA MCP602 can amplify the signal is 4.9 V.

By the same principle, the graphs of the input and output voltage versus time were plotted in the range of input signal amplitudes from 10 mV to 50 mV with 10 mV steps (figure 4) to check the correct operation of the circuit in the weak signal amplification mode.

![Amplifier MCP602 Characteristics](image)

**Figure 4.** The graph of the dependence of the input and output voltage on time in the range of input signal amplitudes from 10 mV to 50 mV; blue color shows graphs of input voltage versus time; the graphs of the output voltage versus time are shown in red.

The figure above shows the operability of the amplifier based on the OA MCP602 at minimum input signal amplitudes up to 10 mV. The values of the output amplitudes correspond to the theoretical ones, there is no signal distortion.

The maximum value of the input voltage should not be set more than 490 mV, since this value is close to the threshold for the appearance of nonlinearity of the output characteristic due to the saturation of the output transistors (figure 5).

![Graph of Maximum Output Signal](image)

**Figure 5.** Graph of the maximum value of the output signal versus the amplitude of the input signal.
The most popular bias circuit is the supply voltage resistor divider (figure 6). It is necessary to bypass the AC bias circuit and add an additional resistor for the $R_{IN}$ input signal to reduce the effects of supply voltage instability. Capacitor $C_2$ is used to filter the ripple on the supply rail, thereby restoring the OA's ability to attenuate common-mode signals and reducing the effect of supply voltage. Resistor $R_{IN}$, which replaces the $R_A/2$ input resistance for AC signals in this circuit, provides DC bias to the amplifier's non-inverting input.

![Figure 6. Decoupled bias non-inverting OA.](image)

The resistances of the resistors $R_A$ and $R_B$ should be kept as low as possible by the power consumption limits. In this case, the minimum possible value of 42 kOhm is selected to reduce the current consumption in the circuit.

3. **Simulation of the peak detector circuit**

There are peak detection circuits that operate on both positive and negative half cycles (and they can vary greatly). This is usually necessary when the signal is asymmetrical, which is very common in audio signals. The peak detector used in magnetoelectric magnetic field sensors has the function of detecting only the positive peak of the AC voltage waveform.

The use of operational amplifiers can significantly improve the parameters of the circuit. With the help of an OA at the input, the parameters of the circuit are improved due to feedback. It is possible to get rid of the problems with the voltage drop across the diode by removing the feedback signal from the capacitor. The output OA should be used as a buffer to measure or process the stored peak voltage; its function is to protect the peak detector circuit from capacitor discharge when operating on a low-impedance load and to amplify the output signal power.

The optimal solution is the MCP602 series OA already used in the amplification circuit. This OA is a fairly popular solution as the input and output elements of the peak detector circuit. Its input current is 1 pA, and its operation is optimal with a capacitor $C = 0.01 \mu F$. This combination results in a drop of only 0.0001 V/s and a slew rate of 7 V/$\mu s$. Even higher parameters can be provided by the LMC660 and LMC6041 CMOS OA with 2 fA input currents. With this design, the main limiting factor is the leakage current of the capacitor and diode. However, the cost of such OAs is much higher than that of the MCP602.

One of the important factors when choosing a diode is the leakage current. Diodes with high leakage currents are not suitable for use in peak detector circuits. Therefore, the diode BAV199 was chosen as the diode. It has $I_l = 3$ nA at 75V reverse voltage. The peak detector circuit is shown in figure 7b.
The previously used scheme is free of most of the drawbacks and it works quite well in practice if the tracking of narrow signal peaks is not required. This is due to the fact that the OA goes into negative saturation when the potential at the input is lower than at the output. Therefore, when the potential at the input to the OA is higher than at the output, the latter is again in saturation, the exit process from which takes a significant amount of time. The improved circuit shown in figure 7b, allows getting rid of this disadvantage.

Figure 7 shows voltage versus time plots of input sinusoidal voltage and output signals processed by peak detectors, where the output signal of the simple circuit is shown in red (figure 7a), and the output signal of the improved circuit of the peak detector is shown in green (figure 7b).

As a result, the graph shows that the voltage drop across the diode was 126 mV. Also comparing the graphs of the output voltage figure 8, it can be seen that the circuit without an OA at the input of the peak detector reaches the peak value much more slowly. This difference is due to the higher leakage current of the rectifying diode than the OA MCP602.
Figure 9. Graphs of input and output voltages versus time in the output voltage range from 500 mV to 5 V.

Figure 9 shows the output signal in the range of output voltages from 500 mV to 5 V. The threshold output voltage, as in the simulation of the amplification circuit, is 4.9 V.

Figure 10. Graphs of input and output voltages versus time in the output voltage range from 500 mV to 5 V.

Figure 10 shows the time dependence. The rise time for the improved peak detector circuit was approximately 1.922 μs, for the simple circuit 5.822 μs. Input noise can be reduced with additional feedback capacitors, but this significantly increases the rise time of the circuit.

It is necessary to plot the graphs of output voltages versus temperature having estimated all the main output parameters of peak detectors. Temperature parameters are the main benefit of the improved peak detector circuitry. Since previous measurements of the temperature stability of the magnetoelectric
current sensor indicated nonlinearity of the output characteristic as a function of temperature, it is the circuitry solutions that can eliminate this temperature effect. Figure 11 shows graphs of output voltages versus temperature. The operating frequency of the circuits is 1 kHz. The temperature range is set from -40 to +85 °C in 10 degree step.

In this circuit, resistor $R_1$ is installed to compensate for the bias currents. Resistor $R_2$ provides the piezoelectric discharge of the magnetoelectric structure. The feedback resistor $R_4 = 90 \, \text{k}\Omega$ and the resistor $R_3 = 10 \, \text{k}\Omega$ creates an amplification $K_u = 10$. This value is selected based on the values of the signal coming from the magnetically sensitive element, which is in the range from 0 to 500 mV. Resistor $R_5$ simulates a load.

A feature of the circuit on the MCP602 OA is a unipolar power supply, which means that only the positive half-wave is amplified and the negative half-wave is not passed through.

A model of the amplitude characteristics of the input and output voltage of the circuit was obtained to determine the real value of the gain of the circuit based on the constructed circuit model $K_u$.

![Graph](image)

**Figure 11.** Output voltage graphs versus temperature in the range from -40 to +85°C in 10 degree step.

The top graph of figure 11 shows a group of outputs from the improved peak detector circuit. Signal shape changes are insignificant, no more than 2% with temperature changes. The numerical value of the output signal is 1 V and corresponds to the amplitude value of the input signal. The use of this circuit in magnetoelectric devices will allow achieving temperature stability of devices in the temperature range from -40 to +85°C.

The lower graph in figure 11 shows a group of output signals from a simple peak detector circuit. Here you can see the changes in the waveform depending on the temperature. The peak amplitude value varies from 0.85 to 0.95 V. The jumps in the voltage discharge of a capacitor with a capacity of 0.01 μF with increasing temperature are even more visible.

As a result of circuit simulation, the improved circuit of the peak detector showed better parameters compared to the simple circuit previously used in laboratory samples of the magnetoelectric current sensor.
4. Simulation of the signal generation circuit

A pulse generator is used in a current sensor circuit to generate an alternating magnetic bias field by an inductor coil to set the operating point of a magnetically sensitive element.

The simulation of the generator circuit was carried out at a frequency of 1200 Hz. The signal generation circuit is shown in figure 12. The use of operational amplifiers can significantly improve the parameters of the circuit. With the help of an OA at the input, the circuit parameters are improved due to feedback. It is possible to get rid of the problems with the voltage drop across the diode by removing the feedback signal from the capacitor. The output OA should be used as a buffer to measure or process the stored peak voltage; its function is to protect the peak detector circuit from capacitor discharge when operating on a low-impedance load and to amplify the output signal power.

![Diagram of the generator circuit on three inverters with separate adjustment of the pulse duration and the pause between them (duty cycle).](image)

**Figure 12.** Generator circuit on three inverters with separate adjustment of the pulse duration and the pause between them (duty cycle).

![Graphs showing the dependence of the voltage on the left plate of the capacitor on time and the output voltage on the generator time on three inverters with separate adjustment of the pulse duration and the pause between them (duty cycle).](image)

**Figure 13.** Graphs of the dependence of the voltage on the left plate of the capacitor on time and the output voltage on the generator time on three inverters with separate adjustment of the pulse duration and the pause between them (duty cycle).

From figure 13 it can be seen that the inclusion of diodes in the circuit makes it possible to separately adjust the duration and the pause between pulses or, at a constant frequency, to adjust the pulse duty cycle.
Figure 14. Graphs of the output voltages on the left plate of the capacitor and the output depending on the temperature in the range from -40 to +85°C in 10 degree step.

Figure 14 shows the change in voltage amplitudes on the left plate of the capacitor. This change is typical for capacitors with temperature changes. In this case, the change is insignificant and varies within 0.2 V. Also, the graph shows the signal at the generator output. The absence of distortion of the waveform, phase shift, and amplitude changes guarantees the performance of the circuit over the entire operating temperature range from -40 to +85°C.

5. Conclusion
The article discusses circuit solutions based on an operational amplifier to improve the parameters of the ME CS. As a result of simulation, data were obtained showing the performance of the amplification circuit in the temperature range from -40 to +85°C. Circuit simulation of the improved peak detector circuit showed better parameters compared to the simple circuit previously used in laboratory samples of a magnetoelectric current sensor. These simulation results suggest an optimistic scenario for the implementation of an improved signal processing circuit, received from the ME structure. When modeling the generation circuit, the expedient use of a generator on three inverters with separate adjustment of the pulse duration and the pause between them (duty cycle) was revealed. The results obtained will significantly improve the output characteristics of the ME structure current sensor and compete with existing analogues.

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