SPICE Modelling of Magnetoresistive Sensors

Boyanka Nikolova[1], Georgi Nikolov[2] and Milen Todorov[3]

Abstract – **In this paper are presented non-linear characteristics of magnetoresistive sensors and methods for their curve fitting. For this purpose is used Curve Fitting Toolbox by MathWorks MATLAB, which provide powerful processing capabilities. The results of curve fitting are used as input data in SPICE model. To creating a SPICE model are necessary ABM (Analog Behavioral Model) sources. They use as input data mathematical expressions from preceding fitting of sensors' characteristics. For this purpose is used National Instruments Multisim.**

Keywords – **Magnetoresistive sensors, Curve fitting, SPICE model, MATLAB, Multisim.**

I. INTRODUCTION

Sensors that monitor properties such as temperature, pressure, strain or flow provide an output signal that is directly related to the desired parameter. Magnetic sensors, on the other hand, differ from most of these detectors as they very often do not directly measure the physical property of interest. They detect changes, or disturbances in magnetic fields that have been created or modified by objects or events.

One of many advantages of using magnetic field for sensing position and distance is that any nonmagnetic material can be penetrated by the filed with no loss of position accuracy. Another advantage is that the magnetic sensors can work in severe environments and corrosive situations because the probes and targets can be coated with inert materials that will not adversely affect the magnetic fields.

Magnetoresistive sensors are well suited to measuring both linear and angular position and displacement in the Earth's magnetic field. For functioning, they require an external magnetic field. Hence, whenever the magnetoresistive sensor is used as proximity, position, or rotation detector, it must be combined with a source of a magnetic field. These sensors offer non-contact operation, high reliability, low and stable offset, low sensitivity to mechanical stress, much more insensitive to vibrations than inductive sensors, high operating temperature, wide operating frequency range, short response time and small size. They therefore provide an excellent means of measuring both linear and angular displacement under extreme environmental conditions, because their very high sensitivity means that a fairly small movement of actuating components in, for example cars or machinery can create measurable changes in magnetic field. Other applications for magnetoresistive sensors include rotational speed measurement and current measurement. The output signal requires some signal processing for translation into the desired parameter.

II. BASE CHARACTERISTICS OF MAGNETORESISTIVE SENSORS

For functioning, magnetoresistive sensors require an external magnetic field. Hence, whenever the magnetoresistive sensor is used as a proximity, position, or rotation detector, it must be combined with a source of a magnetic field. Usually, the field is originated in a permanent magnet, which is attached to the sensor. When the sensor is placed in the magnetic field, it is exposed to the fields in both the *x* and *y* directions. The sensor operates like a magnetic Wheatstone bridge measuring nonsymmetrical magnetic conditions [1, 2, 3].

In a Giant Magnetoresistance (GMR) sensors, the resistance of two thin ferromagnetic layers separated by a thin non-magnetic conducting layer is changed if the magnetic moments of the ferromagnetic layers are changed from antiparallel to parallel. Layers with parallel magnetic moments display less scattering at the interfaces, longer mean free paths, and lower resistance than the layers with antiparallel magnetic moments. The layers must be thinner than the mean free path of electrons (typically lower than 10 nm); if not, the spin-dependent scattering cannot be a significant part of the total resistance. The structures used in GMR sensors are unpinned sandwiches, antiferromagnetic multilayers, and spin valves.

Colossal Magnetoresistance (CMR) sensors under certain conditions undergo a semiconductor-to-metallic transition with the application of a magnetic field of a few teslas (tens of kilogauss). The size of the resistance ratios is 103% – 108%.

The Anisotropic Magnetoresistive (AMR) sensors are suitable for use in the measurement of magnetic fields in the range up to 200 μT. These sensors are made of a Permalloy (NiFe) thin film deposited on a silicon wafer and are patterned as a resistive strip. During deposition of the Permalloy strip, a strong external magnetic field is applied parallel to the strip axis. By doing this, a preferred magnetization direction is defined within the strip.

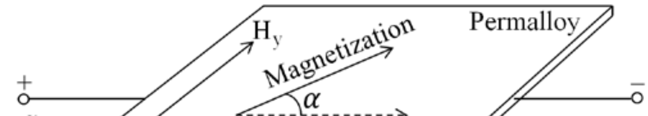

Fig. 1. The magnetoresistive effect in Permalloy.

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The properties of AMR films cause the resistance to change by 2-3% in the presence of an external magnetic field.

In absence of any external magnetic field, the magnetization always points into this direction. In Fig.1 this is assumed to be the *x*-direction, which is also the direction of current flow. An AMR sensor now relies on two basic effects:

1. The strip resistance R depends on the angle α between the direction of the current and the direction of the magnetization;
2. The direction of magnetization and therefore α can be influenced by an external magnetic field H_y, which is parallel to the strip plane and perpendicular to the preferred direction.

When no external magnetic field is present, the Permalloy has an internal magnetization vector parallel to the preferred direction and $\alpha = 0^o$. In this case, the strip resistance R has its maximum value R_{max}. When an external field H_y is applied, the internal magnetization vector of the Permalloy will rotate around an angle α. Resistance reaches its minimum value R_{min} at high field strengths because angle $\alpha = 90^o$. Eq. 1 gives the functional dependence between the resistance and the angle:

$$R = R_0 + \Delta R \cos^2 \alpha \,, \tag{1}$$

where $R_0 = R_{min}$ and $\Delta R = R_{max} - R_{min}$. Function R versus H_y is:

$$R = R_0 + \Delta R \left(1 - \left(\frac{H_y}{H_0} \right)^2 \right). \tag{2}$$

H_0 is parameter, which depends on material and geometry of the strip. Eq. 1 is defined for field strength magnitudes of $H_y \leq H_y$. R_0 and ΔR are also parameters of material. For Permalloy, ΔR is in the range of 2 to 3% of R_0.

Because quadratic Eq. 2 it is obvious that this characteristic is non-linear and each value of R is not associated with unique value of H.

The magnetoresistive effect can be linearized by depositing aluminium stripes (Barber poles), on top of the Permalloy strip, at an angle of 45º to the strip axis (Fig. 2). Because a higher conductivity of aluminum than Permalloy, the effect is rotation of current direction by 45º. Thus the angle between the magnetization and the electrical current is changed from α to $(\alpha - 45^o)$.

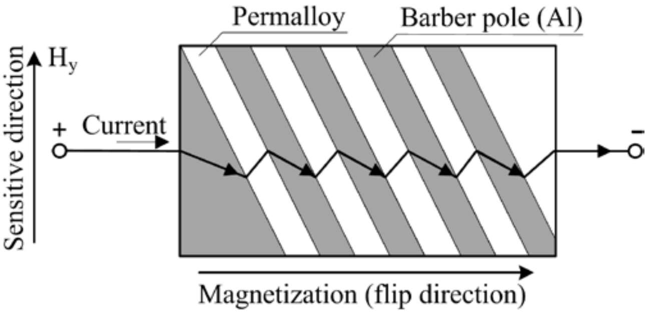
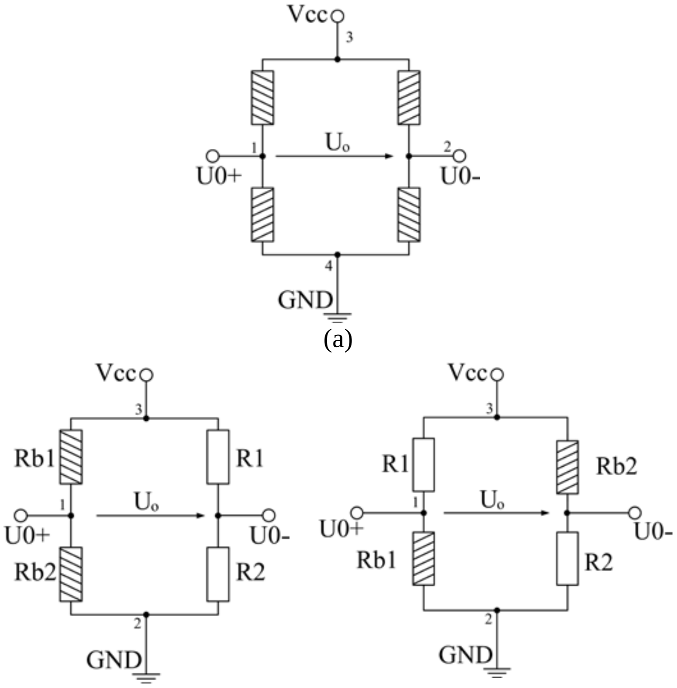


Fig 2. Linearization of the magnetoresistive effect.

AMR sensors are usually used in a Wheatstone bridge configuration with diagonally opposite sensors having barber pole orientations of ±45º (Fig. 3). This arrangement helps to:

- reduce the temperature drift of the sensor;
- increase the sensitivity of the sensor.

The best results are obtained from a Wheatstone bridge configuration when a current source rather than a voltage source drives the bridge. Use of a current drive doubles the bridge linearity and, in the ideal case, the temperature dependence is reduced [1, 3, 6].



(a)

(b)

Fig. 3. Types of Wheatstone bridge:
(a) for full bridge sensors, (b) for half bridge sensors

Conventional Wheatstone bridge signal conditioning circuits can be used to process the AMR bridge. The bridge sensitivity and zero offset are proportional to the bridge voltage, so it is important to use a well-regulated supply with low noise and good temperature stability.

III. PARAMETRIC FITTING WITH MATLAB LIBRARY MODELS

Parametric fitting (Table I) involves finding coefficients (parameters) for one or more models that fit to data. The data is assumed to be statistical in nature and is divided into deterministic and random components. The first component is given by a parametric model and the second one is an error, which represents random variations in the data that follow a specific probability distribution. The model is a function of the independent variable and one or more coefficients [7, 8].

After fitting data with one or more models is important to evaluate the goodness of fit. The first step for that is a visual examination of the fitted curve displayed in Curve Fitting Tool.

Beyond that, the toolbox provides these methods to assess goodness of fit:

- Residual analysis;
- Goodness of fit statistics;
- Confidence and prediction bounds.

TABLE I
LIST OF LIBRARY MODELS FOR CURVE FITTING

Library Model	Description
Distribution	Distribution models such as Weibull.
Exponential	Exponential function and sum of two exponential functions.
Fourier	Up to eight terms of Fourier series.
Gaussian	Sum of up to eight Gaussian models.
Interpolant	Interpolating models, including linear, nearest neighbour, cubic spline, and shape-preserving cubic spline.
Polynomial	Polynomial models, up to degree nine.
Power	Power function and sum of two power functions.
Rational	Rational equation models, up to 5th degree/5th degree (i.e., up to degree 5 in both numerator and denominator).
Sin	Sum of up to eight sin functions.
Spline	Cubic spline and smoothing spline models.

IV. MODELLING OF MAGNETORESISTIVE SENSORS

A. Structure of the SPICE model

The ABM feature of SPICE can be used to make flexible descriptions of electronic components in terms of a transfer function or look-up table. The basic structure of the magnetoresistive sensors ABM model using Wheatstone half bridge is shown in fig. 4.

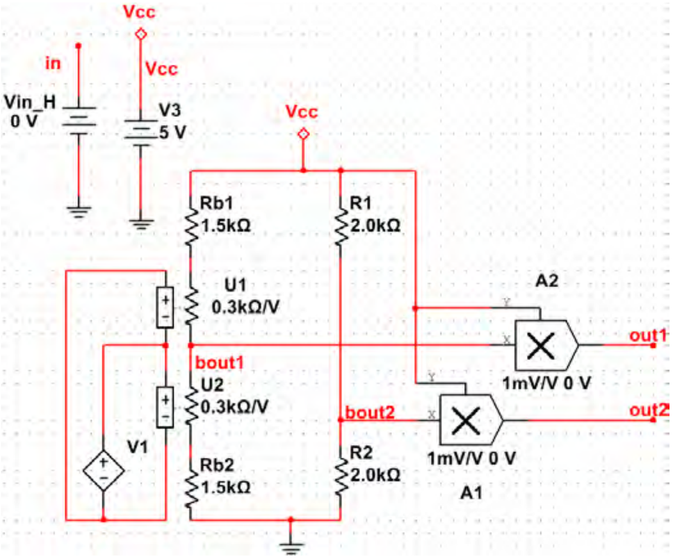


Fig. 4. SPICE Model of Magnetoresisitive Sensors

The main parts of the proposed model are:

1. V1 – ABM voltage source. The polynomial expression is specified as a mathematical equation which presented transfer function of the sensors. The obtained output voltage is equivalent to the relative change of resistance over the simulated magnetic field.

2. U1 and U2 – The resistance of this voltage controlled resistor is controlled by the voltage that is applied across the "+" and "-" terminals.

3. Rb1 and Rb2 – resistors using for modelling the nominal resistance of magnetoresistive elements of the sensor.

4. R1 and R2 – the value of the resistors is equal to the bridge resistance given in the datasheets.

5. A1 and A2 – Multipliers using for calculating the output voltage of the bridge according to the supply voltage.

B. Curve fitting of transfer characteristic of AMR Sensor KMY 21 M

After fitting data with one or more models is very important to evaluate the goodness of fit. The two stages are: visual examination of the fitted curve and estimation of numerical results. Plotting residuals and prediction bounds are graphical methods. They are more beneficial and aid visual interpretation, while numerical results are more narrowly focused on a particular aspect of the data and often try to compress that information into a single number [4, 5, 9].

For fitting models of transfer characteristic of AMR Sensor KMY 21 are chosen 9th and 8th degree polynomial fits. The data, fit, prediction bounds and residuals for fitting are shown on Fig. 5.

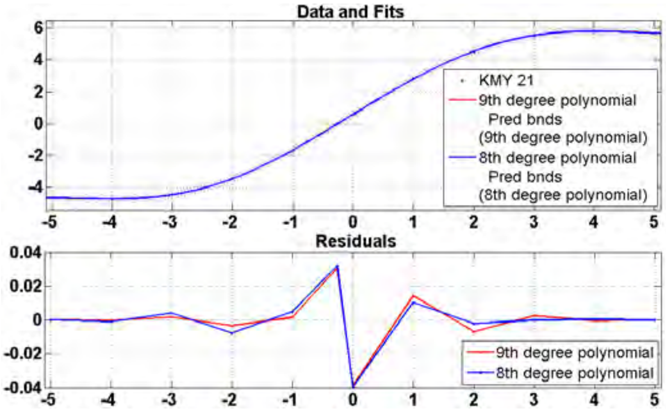


Fig. 5. Graphical results of curve fitting of transfer characteristic of AMR Sensor KMY 21.

TABLE II
NUMERICAL RESULTS OF CURVE FITTING

Fit	Polynomial	
Degree	9th	8th
Coefficients:		
p1	-1.975e-005	-1.172e-005
p2	-1.256e-005	-7.187e-005
p3	0.0009386	0.0005617
p4	0.0006047	0.006016
p5	-0.01049	-0.007533
p6	-0.008237	-0.2229
p7	-0.1276	0.008468
p8	0.01255	5.008
p9	4.866	0.4788
p10	0.4727	–
Goodness of fit:		
SSE	0.007368	0.02864
R-square	1	1
Adjusted R-square	1	0.9999
RMSE	0.0607	0.09771

From Fig. 5 and Table II it is clear that the 9th degree polynomial fit gives better results than 8th degree polynomial fit (lower values of Sum of Squares due to Error (SSE), and Root Mean Squared Error (RMSE), which are closer to ideal case value – 0).

C. Simulation Results

The design approach for magnetoresistive sensors modelling described above is implemented for AMR Sensor KMY 21 M. The equation of ABM source V1 is 9th degree polynomial with coefficients given in Table II. Typical values for the circuit components according to datasheets [6] are $R_1 = R_2 = 2\ \mathrm{k\Omega}$ and $R_{b1} = R_{b2} = 1{,}5\ \mathrm{k\Omega}$ with temperature coefficient of resistance of 0,0032 1/°C.

Fig. 6 illustrates the simulation results of the transfer characteristic of AMR Sensor KMY 21 M, using the SPICE simulator. The error of the model is formed only from the accuracy of the curve fitting, because the characteristic is described by mathematical polynomial equation. Therefore using the proposed model, the sensor can be simulated and used not only in the linear region of the transfer characteristic but in relatively large scale of input magnetic fields.

The simulation results of temperature simulation of the input offset voltage is shown on fig. 7.

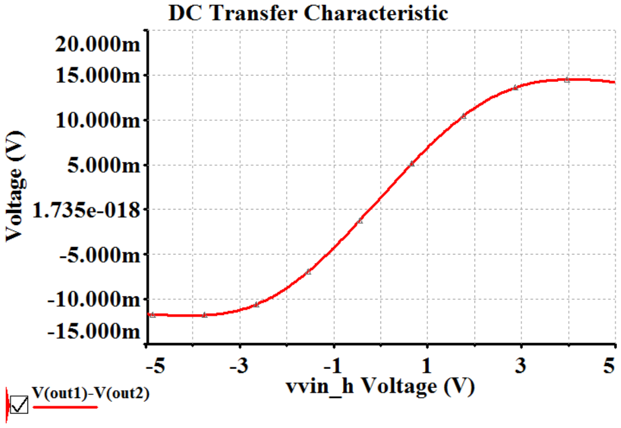


Fig. 6. Transfer characteristic of AMR Sensor KMY 21 M.

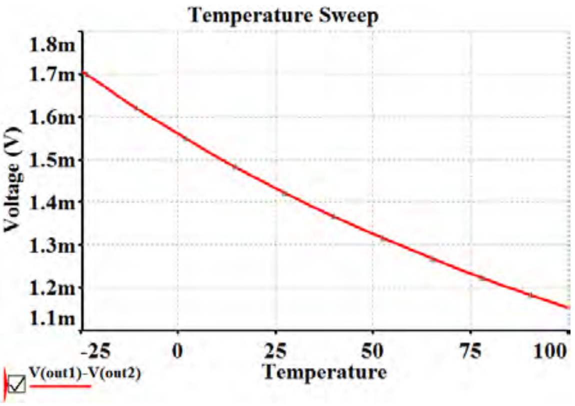


Fig. 7. Offset temperature dependence of AMR Sensor KMY 21 M.

In Table III are summarized main sensors' parameters and appropriate conditions for their simulations.

TABLE III
SENSOR SPECIFICATION

Parameter	Simulation Condition	Value
Supply Current	$I_{CC}\ (V_{cc})$	1,67 mA
Output voltage range	$\Delta V_o = (V_{out\,\max} - V_{out\,\min})$ $H_y = -5\ \mathrm{kA/m} \div +5\ \mathrm{kA/m}$	25,86 mV
Offset voltage	$V_{off} = V_{out}\ (H_y)$ $H_y = 0$	1,42 mV
Sensitivity	$S = \dfrac{dV_{out}}{dH_y}$ $H_y = -1\ \mathrm{kA/m} \div +1\ \mathrm{kA/m}$	5,57mV/kA/m
Temperature coefficient of offset	$TCV_{off} = \dfrac{V_{off}(T_2) - V_{off}(T_1)}{T_2 - T_1}$ $T_1 = -25°\mathrm{C};\ T_2 = +125°\mathrm{C}$	-4,16 µV/°C
Temperature coefficient of amplitude	$TCV_o = \dfrac{\Delta V_o(T_2) - \Delta V_o(T_1)}{(T_2 - T_1)\Delta V_o(T_1)}$ $T_1 = -25°\mathrm{C};\ T_2 = +125°\mathrm{C}$	-75,58 µV/°C

V. CONCLUSION

In this paper a SPICE behavioral model of magnetoresistive sensors is presented. An systematic approach for implementing curve fitting models and methods is applied in order to achieve equation that precisely describe sensor's transfer function. The main benefits of proposed model is that by using only one ABM voltage source many sensors' parameter can be defined like sensitivity, offset, nonlinearity and input range. The proposed modelling approach is suitable to predict behavior of other type of magnetoresistive sensors.

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