

Intellectualization of Microelectronic Sensors Based on Elements on Surface Acoustic Waves

Ya.I. Lepikh^{1,*}, V.V. Yanko¹, P.O. Snigur¹, A.P. Balaban¹, A.V. Agarkov²

¹ Interdepartmental Scientific-Educational Physics and Technical Center of MES and NAS of Ukraine at the Odesa I.I. Mechnikov National University, 2, Dvoryanska st., 65082 Odesa, Ukraine

² M.K. Yangel State Enterprise "KB "Pivdenne", 28, Shevchenko Ave., 40001 Dnipro, Ukraine

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Using the example of an acoustoelectronic sensor of linear displacements on surface acoustic waves (SAW), a method of intellectualization of microelectronic sensors has been developed, the feature of which, in particular, is the frequency type of the output signal. The structure diagram of the SAW sensor with the intelligent support unit (ISU) is described. The ISU receives input data from elements on the SAW of the sensor, processes them according to the developed algorithm of intellectual support in two modes of operation, which provide high metrological characteristics, as well as interface and service functions. In the programming of embedded processors, the used C/C++ language is implemented by a binary array of const float variable constants with a floating point defined as const float Dat[N][T + 1].

Keywords: Sensors on surface acoustic waves, Intellectualization, Microcontroller, Algorithm

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1. INTRODUCTION

Development and improvement of microelectronic sensors of various functional purposes and built on the basis of various physical, chemical and biological principles and effects is carried out in two main directions: improvement of metrological characteristics and their intellectualization. The analysis shows that despite the existing possibilities of improving sensors based on traditional principles, fundamental solutions to the problem of creating sensors of a new generation – intelligent sensors, lie in the way of using new principles of their construction. One of them is acoustoelectronic based on surface acoustic waves (SAW) [1, 2]. One of the fundamental features of sensors of this type is the frequency type of the output signal and the change in its output parameters in real time depending on the change in the parameters of the measured quantity. This simplifies the possibilities of conjugating sensor elements with microprocessor technology and their intellectualization by embedding cybernetic devices, performing algorithmization of measurement methods using modern methods of machine learning and data analysis. At the same time, the maximum quality of the primary measured signal is achieved due to a smaller number of signal conversions, in particular according to the analog-digital scheme. This task – the development of a method of intellectualization of SAW sensors using the example of a linear displacement sensor – was solved in this work.

2. THE DESIGN OF THE DISPLACEMENT SENSOR ON SURFACE ACOUSTIC WAVES

Improving the characteristics of SAW sensors is based on the use of acoustoelectronic phenomena, especially those that occur during the propagation of SAW in piezoelectrics and layered structures [1-2]. In addition to high metrological characteristics, sensors of this type, due to their characteristic frequency type of the output signal,

differ in speed and ease of conjugation with microprocessor technology, which ensures their intellectualization and operation in "online" mode.

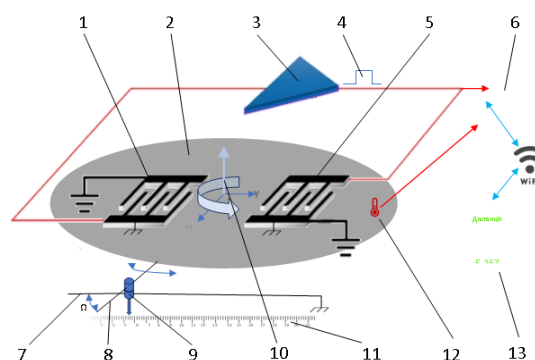


Fig. 1 – Diagram of a movement sensor with an intelligent support unit (ISU), where: 1 – fixed counter-pin transducers (CPT) receiving; 2 – piezoelectric substrate – rotating sound pipe; 3 – a linear amplifier in the feedback pipe ensures the generation of a measuring signal with a frequency that depends on the ultrasonic delay line; 4 – measuring signal with frequency f_{dist} ; 5 – fixed CPT transmission; 6 – a microcontroller with a wireless communication unit; 7 – guiding fixed movement of the hinge; 8 – a guide of a movable joint that rotates with a piezoelectric substrate and a measuring rod; 9 – hinge; 10 – axis of rotation of the measuring rod; 11 – a scale for controlling the distance of movement; 12 – temperature sensor controlling the microcontroller; 13 – mobile terminal

Fig. 1 shows the structural diagram of the linear displacement sensor on the SAW.

The main information parameter of such a sensor, as mentioned above, is the frequency of the f_{dist} signal (Fig. 1, item 4). This signal is generated by a circuit with a linear amplifier (Fig. 1, pos. 3) and an element that sets the frequency in the feedback circuit – a delay line on the

* ndl_lepikh@onu.edu.ua

characteristic curve (Fig. 1, pos. 1, 5, 3). The SAW propagation medium is anisotropic, as a result of which the SAW speed (delay time) depends on the direction of their propagation, and, as a result, on the angle of rotation Ω between the fixed and rotating parts of the structure [3]. Accordingly, the frequency of generation depends on the orientation of the longitudinal axis of the CPT relative to the crystal axis of the single-crystal piezoelectric – sound pipe in the SAW acoustic system (Fig. 1, item 2), namely the angle Ω . The design of the sensor provides a smooth, damped change of this angle by turning the measuring rod around the axis (Fig. 1, item 10). The dependence of the frequency on the rotation of the rod is monotonic, quasi-linear, weakly and monotonically dependent on temperature. The sensor includes a vernier device (Fig. 1, item 7, 8, 9), which converts the rotation of the rod into a linear movement of the pin pointer along the distance control scale (Fig. 1, item 11).

3. ISU

The ISU includes: a microcontroller with a wireless communication unit (Fig. 1, item 6), a mobile terminal that monitors the operation of the distance sensor via a wireless communication channel (can be replaced by a valid consumer of measurement information), digital temperature sensors as close as possible to points around the structure on silicon (Fig. 1, item 12). The BIS receives input data from the sensor elements, processes them according to the algorithm of intelligent support formalized by the program embedded in the microcontroller, and forms the output data in the required form. The algorithm provides two main modes of operation of the sensor: basic and service metrological.

Input data of the intelligent support algorithm:

- a rectangular analog signal containing information about the main parameter of the fdist frequency sensor. The analog-to-digital conversion of this signal takes place with the resources of the microcontroller, it can be implemented by alternative algorithmic methods, which affects the quality of metrological characteristics of the sensor as a whole.

- digital signal from temperature sensors.

- control signals from the mobile terminal (user interface) are logical and numerical. They are used to switch modes and change the parameters of the sensor, request the output of useful and service metrological data.

- digital metrological information entered in official metrological mode.

The output data of the intelligent support algorithm are as follows:

- a digital signal that contains the data of the controlled movement;

- digital signals containing service data;

- digital metrological information displayed in service metrological mode.

4. METROLOGICAL CHARACTERISTICS AND SENSOR PARAMETERS THAT REQUIRE INTELLECTUALIZATION

4.1 Nonlinear Dependence of the Generation Frequency on the Resulting Measuring Distance (Displacement)

The dependence of the frequency on the distance is the main metrological characteristic of the sensor. There is no economically justified method of obtaining an analytical expression of this dependence. The problem can be solved by memorizing empirically obtained characteristics. Microprocessor digital technologies can be used quite effectively for this [4, 5]. It is preferable to use algorithms that require less memory. Algorithms for memorizing empirical dependencies, based on mathematical methods of approximation of nonlinear functions, are more economical, since less data is required for this, because part of the data is given analytically. The most common methods of approximation of nonlinear functions are:

- piecewise linear approximation – presentation of the approximated function by segments of straight lines;
- polynomial approximation – representation of a nonlinear characteristic using a power series;
- approximation using various types of transcendental functions.

Algorithms for memorizing nonlinear dependencies, which are often used in metrological instrumentation, are as follows:

- tabular – direct fixation of dependence by points (uses memory the least economically, with the required accuracy);

- piecewise-linear – based on the mathematical method of the same name (quite economical and flexible algorithm);

- non-linear and piecewise non-linear – is based on appropriate mathematical methods (the most economical, but the most complex algorithm).

4.2 Temperature Dependence of the Main Metrological Characteristics of the Sensor

Since ST-cut piezoelectric quartz is used as a monocrystalline piezoelectric of the sound pipe in this sensor, the change in the characteristics of the sensor depending on the temperature of this functional element can be neglected.

Therefore, the dependence of the sensor characteristics will be determined mainly by the thermal expansion of the structural elements, the temperature characteristics of the electroradio elements, etc. In this case, compensation of temperature dependence is also carried out by memorizing empirically obtained data.

At the same time, it is necessary to take into account:

- whether the temperature dependence is a linear function for the required accuracy. And here you can apply the piecewise linear method of temperature compensation with one section, i.e. temperature coefficient;

- whether the dependence on temperature changes over the measuring range. If the temperature dependence is a function of the rotation angle of the sensor rod, it will be necessary to memorize more data to fix this dependence.

4.3 User Interface and Auxiliary Functions of ISU

In addition to the main functions that provide metrological tasks, ISU performs interface and service functions. These functions serve to ensure the adjustment

and improvement of the sensor design, the selection of operational parameters for the current practical task of the sensor application:

- user interface: a multifaceted external menu of functions has been developed, based on graphical control elements and intelligent information presentation elements;
- existence of a regime for research and collection of metrological information;
- availability of modes for selecting metrological and ergonomic parameters necessary for the current task;
- recording of selected settings on non-volatile memory.

The full implementation of these functions requires the creation of software for a device that works with ISU via wireless communication. It can be a specialized device (not general control, standard) according to the principle of "remote control".

5. ALGORITHMIC METHODS OF IMPLEMENTATION OF PIECEWISE LINEAR APPROXIMATION FOR METROLOGICAL SOLUTIONS IN ISU

5.1 Task Formalization

The formalization of a two-dimensional piecewise-linear function taking into account temperature instability at the program level (in the programming of embedded processors, the C / C++ language is mainly used, the semantics of which we will adhere to) is implemented by a two-dimensional array constant variables of type *const float* (with floating point), which is defined as *const float Dat[N][T+1]*. That is, an array of length $T+1$ arrays of length N , where N – the number of approximating points of dependence of the distance on the frequency; T is the number of temperature values at which experimental dependences were obtained. The $Dat[N][0]$ array is an independent variable, a set of frequency values selected for approximation, monotonically increasing as the index increases. Other arrays: $Dat[N][1]$, $Dat[N][2]$, ..., $Dat[N][T]$ are sets of distance values measured at the corresponding temperature values. The temperature values at which the experimental dependences were recorded are formalized by a constant one-dimensional array $Temper [T]$. Variables with the same values of the index j : $Dat[j][0]$, $Dat[j][1]$, ..., $Dat[j][T]$ are related and implement a functional discrete dependence at the j -th point.

- $Dat[j][0]$ – j -th frequency value;
- $Dat[j][1]$ – corresponding to the j th frequency value is the distance value measured at temperature the minimum of the set of temperatures;
- $Dat[j][2]$ – corresponding to the j -th value of the frequency, the value of the distance, measured at the temperature next to the minimum from the set of temperatures.
- $Dat[j][T]$ is the distance value corresponding to the j th frequency value, measured at the maximum temperature from the set of temperatures.

This data is constant to the embedded microcontroller program and can be adjusted or replaced later. The data is obtained using algorithmized measurement pro-

cedures in the official metrological mode. It seems appropriate to write auxiliary programs to automate the process of preparing metrological data and entering them into the text of the program, which is "stitched" into the microcontroller, for example, in the PYTHON language. In this case, it is possible to do without the involvement of the programmer of embedded systems in case of possible changes in the design. In addition, such a program can optimize the division into linear sections of the approximating dependence in the case of available detailed data, or manage the measurement process of their optimal acquisition. Fig. 2 shows an illustration of the process of formalization of input data (for simplification only for one temperature from the $Temper [T]$ array, for example with the index k).

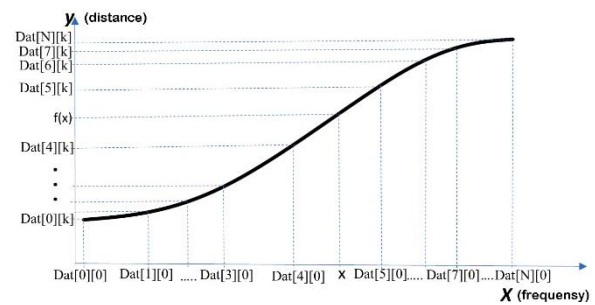


Fig. 2 – Adaptation of the piecewise linear approximation method for linear displacement sensor embedded software

5.2 Splitting the Dependence Graph Into the Required Number of Linear Segments

The following division principles are possible:

- uniform for one of the variables (reduces the required memory, increases the computing load);
- a variable step, where more linear sections are more extended.

Point selection criterion (Fig. 3) – for any point of the approximating segment, the vertical distance (parallel to the y axis) to the curve being approximated does not exceed the specified accuracy

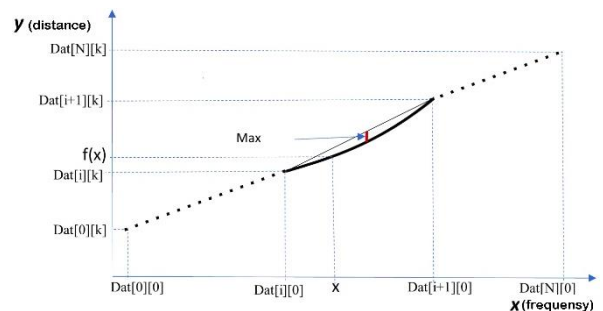


Fig. 3 – Criterion for selecting points of approximating segments on the approximating curve

5.3 Algorithm for Implementation of Piecewise Linear Function

On Fig. 4 shows the block diagram of the implementation algorithm of the piecewise linear function.

Definition:

N – the number of approximation points, which coincides with the length of data presentation arrays (the

number of approximating segments $N - 1$ (See clause 5.2.);

Int getFreq () - the function of obtaining the current value of the frequency;

float GetTemper () - the function of obtaining the current temperature value;

Int TemperDiap (float) - the function for determining the temperature range to which the current temperature from the temperature sensor falls returns the number of the temperature range N_i , such that: $\text{Temper}[N_i] < t < \text{Temper}[N_i + 1]$;

const Float Dat[N][T + 1] - constant array of linearization data (See clause 5.1.);

const Int T is a constant - the number of temperature values;

const Int Temper [T] - an array of temperature constants;

float x - a variable for storing the current frequency from the frequency meter (See clause 5.2.);

float t - a variable for storing the current temperature from the sensor (See clause 5.2.);

int N_i - variable for storing the temperature range number;

float y₁ - a variable for storing the value of the calculated distance at the lower point of the temperature range;

float y_h - variable for storing the value of the calculated distance at the upper point of the temperature range (maximum temperature in the range);

float y - a variable for storing the value of the calculated distance (the final result of the algorithm);

void OutDist (y) is a function for outputting the distance value and scaling the distance scale.

The algorithm is organized as an infinite loop (there is no “stop” block), which is typical for embedded programming

The start is followed by the input of data from physical sources - the **GetFreq ()** and **GetTemper ()** functions are implemented. Next, the **TemperDiap ()** function is used to determine which temperature range the current temperature falls into from the predefined ones. Next (three blocks), a cyclical search for the linear section where the value of the input frequency falls is organized.

Next (output **Truth** block analysis conditions) using the found values of **i**, the values of the distance between two adjacent temperature values, extreme for the found range, are calculated. Next, the value of the distance is calculated taking into account the current temperature. This value after scaling (by changing the distance between the axis of rotation of the measuring rod (Fig. 1, item 10) and the guide of the fixed movement of the hinge (Fig. 1, item 7) it is possible to change the proportion between the angle Ω and the distance) is output to the wireless channel, mobile terminal (Fig. 1, item 13). Calculations use the formula for the segment of a linear function: the increment of the function is equal to the increment of the argument multiplied by the proportionality factor. The coefficient of proportionality of a segment of a linear function is equal to the ratio of the difference in the coordinates of its extreme points (constant data). The result is the sum of the increment of the function and the constant value at the lower point of the segment.

6. CONCLUSIONS

The proposed and developed method of int electualization of microelectronic sensors on PAH, tested on the sensor of linear displacements, is new and allows solving one of the complex problems in the field of sensors.

The modern microprocessor technology and intelligent support algorithms used in the work made it possible to solve the problems of obtaining high metrological characteristics, including the correction of temperature dependences of the sensor elements.

The obtained solutions can be used in the intellectualization of microelectronic sensors built on other physical principles.

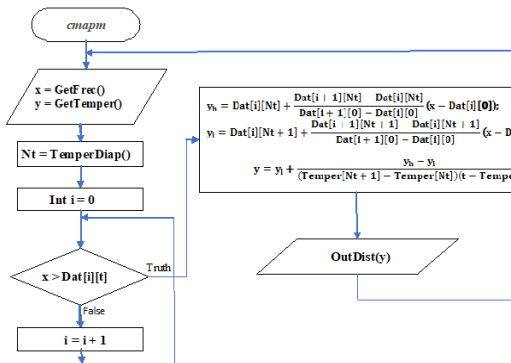


Fig. 4 - Block diagram of the implementation algorithm of the piecewise linear function

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Інтелектуалізація мікроелектронних датчиків на основі елементів на поверхневих акустичних хвиляхЯ.І. Лепіх¹, В.В. Янко¹, П.О. Снігур¹, А.П. Балабан¹, А.В. Агарков²¹ *Міжвідомчий науково-навчальний фізико-технічний центр МОН і НАН України при ОНУ імені І.І. Мечникова, вул. Дворянська, 2, 65082 Одеса, Україна*² *ДП "КБ"Південне" ім. М.К. Янгеля, пр. Шевченка, 28, 40001 Дніпро, Україна*

На прикладі акустoeлектронного датчика лінійних переміщень на поверхневих акустичних хвилях (ПАХ) розроблено метод інтелектуалізації мікроелектронних датчиків, особливістю яких, зокрема, є частотний вид вихідного сигналу. Описана структурна схема датчика на ПАХ з блоком інтелектуального забезпечення (БІЗ). БІЗ отримує вхідні дані від елементів на ПАХ датчика, обробляє їх за розробленим алгоритмом інтелектуального забезпечення в двох режимах роботи, що забезпечують високі метрологічні характеристики, а також інтерфейсні та сервісні функції. В програмуванні процесорів, що вбудовуються, використана мова C/C++ реалізована двовимірним масивом констант змінних типу `const float Dat[N][T + 1]`, що визначається як `const float Dat[N][T + 1]`.

Ключові слова: Датчики на поверхневих акустичних хвилях, Інтелектуалізація, Мікроконтролер, Алгоритм.