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DEVELOPMENT OF THE BASIC CAPACITIVE ACCELEROMETERS MODELS BASED ON THE VHDL-AMS LANGUAGE FOR THE CIRCUIT LEVEL OF COMPUTER-AIDED DESIGN

In the article, the basic VHDL-AMS models of MEMS-based capacitive accelerometers were developed. The models were designed for two basic types of capacitive accelerometers, namely lamellar and counter-pivotal. The developed models allow us to determine the source of electrical capacitive accelerometers depending on the incoming mechanical and structural parameters and were constructed for MEMS CAD at the circuit level. The circuit level of MEMS development requires an analysis of the total integrated device electric circuits. For this purpose, all the MEMS components should be written in the specific software systems, which would be understandable for the software system. Taking into account that MEMS devices operate on different physical principles, certain difficulties may arise during the electrical analysis, that is, the work of mechanical or other devices need to be described with the help of electric parameters. In the general case, the method for building the VHDL-AMS model of the MEMS-based capacitive accelerometer is needed construction of the simplified mechanical model, and then a simplified electrical model. On the basis of the simplified models, the VHDL-AMS model of electromechanical MEMS devices has been developed. In the article, the method of automated synthesis and mathematical models using the VHDL-AMS language, which is based on the method of electrical analogies were described. They use systems of ordinary differential equations and partial differential equations to determine the relationships between input and output parameters. The sequence and quantity of used differential equations are determined by the physical principles of operation of the MEMS element and the number of energy transformations, which allows increasing the level of automation of synthesis operations compared to existing methods. The results of the basic lamellar and counter-pivotal capacitive accelerometers are also shown. This enables to conduct research and analysis of its parameters and investigate the output electric parameters dependence on the input mechanical ones.

Keywords: VHDL-AMS, CAD, circuit level, capacitive accelerometers, modelling.

Introduction

The modern economy requirements for technical devices are strict, namely: low prices, small sizes, low power consumption, high reliability, versatility, environmental safety and others. One of the ways to ensure such strict requirements is the large-scale application of the integrated technologies that use achievements from different science areas.

Analysis of recent research and publications. Microelectromechanical systems (MEMS) are representatives of the following heterogeneous interdisciplinary integrated technologies [1]. MEMS are already widely used in technical devices for different functional purposes [5], [7], [9]. MEMS elements usage for acceleration measurement is of particular practical interest [3], [5], [13], [16]. However, due to MEMS heterogeneity, some difficulties arise in the process of their computer-aided design, which involves use of the block-hierarchical approach [5], [7], [17], [19] with the peculiarities and specifics at the system, circuit and component development levels.

Mathematical models of CAD circuit level have their peculiarities and features. In particular, as a rule, they include systems of ordinary or algebraic differential equations. Such models typically do not require large amounts of resources, but, in this case, the accuracy of the output results is also low, which is quite sufficient at this design level. This mathematical apparatus can be successfully used for constructing models at the circuit level of microelectromechanic systems design.

Taking into account that MEMS are integrated devices and there are software tools widely used for designing such devices, accordingly, they should be used for microelectromechanical systems development. Therefore, for MEMS design and analysis at the circuit level the modification of the VHDL language, namely: language VHDL-AMS [2] is widely used. The VHDL-AMS language allows to build heterogeneous MEMS elements models and analyse their performance [4], [6], [10]. This feature and the main difference of VHDL-AMS from VHDL hardware description language is that it gives the opportunity to describe the performance of the integrated devices, where incoming and output signals can be of any nature (not just electrical as it is in VHDL), which is characteristic of microelectromechanical systems.

Modern scientific literature gives a number of VHDL-AMS models of capacitive accelerometers [15], [20], [21], [22], but their usage as a base for design automation is associated with a number of difficulties. This needs a model and its code simplicity, code presence, ability to modify the model, ability to increase its functionality etc.

The *aim of the work* is to increase the efficiency of the automated design of capacitive microelectromechanical accelerometers of different designs at the circuit level by developing basic models based on the VHDL-AMS language. The designed models of capacitive MEMS accelerometers allow to establish the dependencies between the output voltage of electric capacitive accelerometers or the output electric current from the input mechanical and structural parameters.

Accordingly, *the object of the study* is the process of automated design of MEMS basic elements on the circuit level based on VHDL-AMS models.

The subject of research is the method of automated synthesis and mathematical models using the VHDL-AMS language, which are based on the method of electrical analogies. They use systems of ordinary differential equations and partial differential equations to determine the relationships between input and output parameters.

The scientific novelty of the obtained results lies in the justification and creation of the method of synthesis of MEMS basic elements VHDL-AMS models on the circuit level of automated design and model of capacitive MEMS accelerometers based on the VHDL-AMS language.

The practical significance of the obtained results is to receive the relationships between the output electrical and input mechanical parameters for typical capacitive microelectromechanical accelerometers and designed algorithms for the synthesis of MEMS devices on the circuit level of computer-aided design.

Research results and their discussion

Development of the basic capacitive accelerometers models. Examples of the basic capacitive accelerometers structures are shown in Fig. 1-2. The specification and technology of their construction are described in detail in [9], [11], [13], [16]. As the basic accelerometers capacitive devices two constructions, namely: lamellar and counter-pivotal have been selected. For example, performance of the capacitive accelerometer, whose lamellar construction is shown in Fig. 1, can be described with the help of the simplified mechanical model that is depicted shown in Fig. 3.

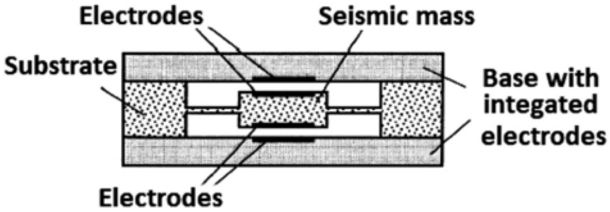

Figure 1. Capacitive accelerometer construction

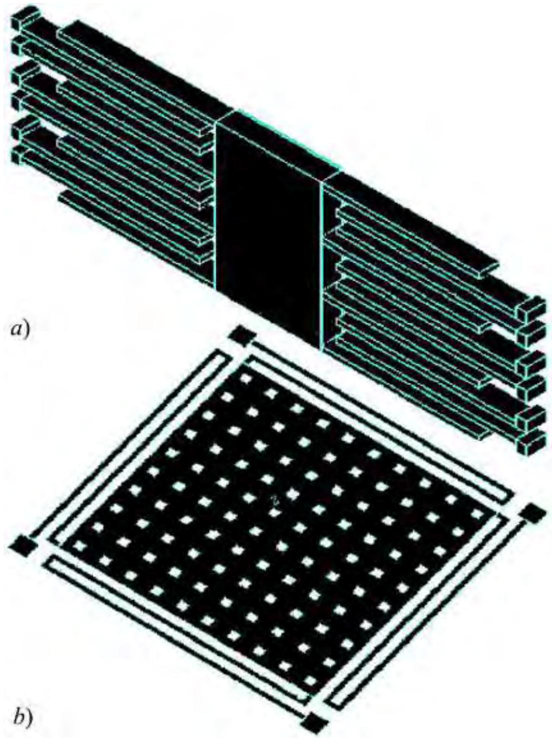

Figure 2. Pectinated acceleration sensor construction (*a*), lamellar capacitive accelerometer construction (*b*)

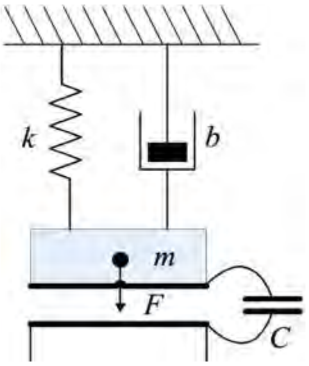

Figure 3. Simplified model of the capacitive accelerometer

In the simplified physical accelerometer construction of the model: m – is seismic mass; F – applied power; k – spring elasticity coefficient; b – damping coefficient; C – electric capacity.

The work of the preceding simplified model is described by a mathematical model, which includes the ordinary differential equation of the second order

$$m\frac{d^2x}{dt^2}+b\frac{dx}{dt}+kx=F\,,\quad F=F_a+F_{el}\,, \tag{1}$$

where x is displacement; F_a – mechanical strength; F_{el} – the force caused by the field. The equation (1) should be completed by the initial conditions of the next type:

$$\frac{\partial x(t=0)}{\partial t}=0\,,\quad x(t=0)=0 \tag{2}$$

In microscale electrostatic force has significant impact on the system functionality, which is shown in Fig. 3. Accordingly, in equation (1) the general force F depends on both mechanical and electronic Fel forces. To determine the electronic force magnitude the following equation is used:

$$F_{el}=C\frac{U^2}{2(d-x)}\,,\quad C=\varepsilon_o\varepsilon\frac{S}{d-x}\,, \tag{3}$$

where S is square plates; U – applied voltage; d – the initial distance between the capacitor plates; ε, ε_0 – dielectric penetrability between the plates of the capacitor and the dielectric penetrability in vacuum.

A similar functional model, which includes equations (1-3), is for integrated capacitive accelerometer design that is depicted in Fig. 3.

An example of the capacitive accelerometer counter-pivotal construction a model of includes the differential equation (1), and the capacity is determined by the following equations:

$$C_1=\frac{\varepsilon_o\varepsilon\, S}{(\delta+x)}\ \text{ and }\ C_2=\frac{\varepsilon_o\varepsilon\, S}{(\delta-x)}\,, \tag{4}$$

where C_1 and C_2 – the capacity between the top and fixed electrodes, capacity between the bottom and fixed electrodes, respectively (Fig. 4).

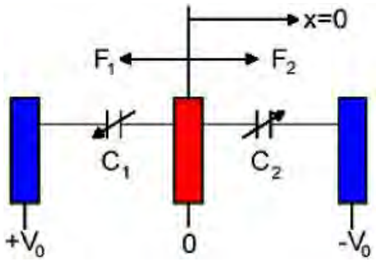

Figure 4. The electric simplified scheme of the counter-pivotal accelerometer

Development synthesis method of the VHDL-AMS models. The circuit level of MEMS development requires analysis of the total integrated device electric circuits. For this purpose, all the MEMS components should be written in the respective software systems [1], [8] , [12], which would be understandable for the software system.

Taking into account that MEMS devices operate on different physical principles, certain difficulties may arise during the electrical analysis, that is, the work of mechanical, hydraulic, acoustic and other devices need to be described with the help of electric parameters.

For solving such problems, as it was already mentioned above, the VHDL-AMS language [1], [8], [12] has been designed. It allows to build VHDL-AMS models for analogous and digital circuits analysis. Every model has its own descripting language and allows to depict the work of the non-electric MEMS devices in the description of the entire electrical circuit.

In the general case, the method for building VHDL-AMS model of capacitive accelerometer is in given Fig. 5 (the accelerometer construction is depicted in Fig. 1). It needs a construction of the simplified mechanical model, and then a simplified electrical model. On the basis of the simplified models the VHDL-AMS model of electromechanical MEMS device has been developed.

While building VHDL-AMS sensors models with other working principles this method should be followed, although it can include a greater number of transducers [18].

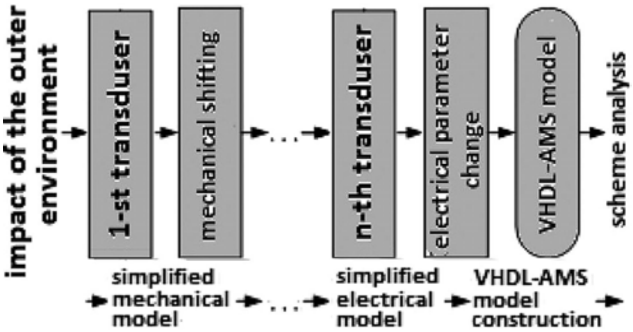

Figure 5. Scheme of synthesis method of VHDL-AMS models for electromechanical MEMS devices

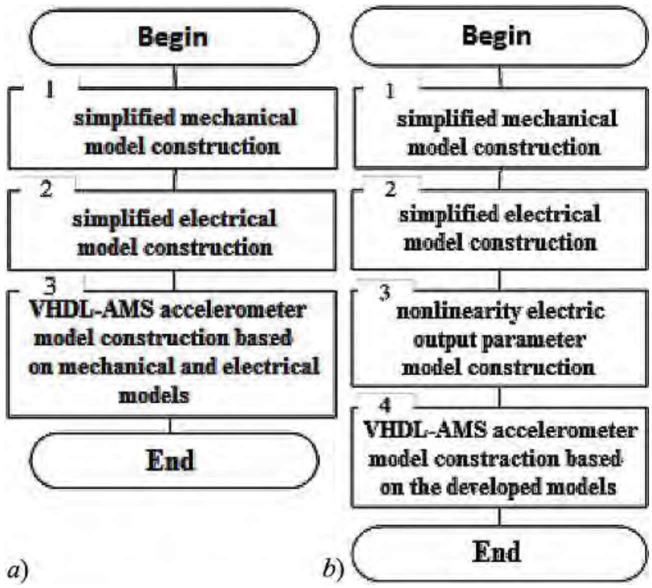

Figure 6. Basic algorithm of the VHDL-AMS accelerometer model (*a*) and the algorithm for constructing its model taking into account the nonlinearity of electric power (*b*)

The peculiarity of the algorithms of constructing of all VHDL-AMS models for sensors with any work principle is that in the end a simplified electrical model of MEMS device should be build, since the electrical circuit can register only the electrical parameters or their modifications. In many cases, electric parameters have changes of non-linear nature. So, in case of increasing the model accuracy, this should be considered and the algorithm in Fig. 6,*a* should be enlarged by a block of study and formalization of nonlinearity electric output parameter of MEMS device stages. The example of the respective algorithm is shown in Fig. 6,*b*.

Construction of VHDL-AMS models of MEMS-basic elements. An example of the developed VHDL-AMS capacitive accelerometer model of lamellar structure, which is described by equations (1-3) is shown in Fig. 7.

```
01 library Disciplines;
02 use Tutorial. extra _ functions.php. all;
03 use Disciplines. electrical _ system. all;
04 use Mechanical_system. all Disciplines;
05 entity DAVACH_ACCEL_CAPAS_Fe is
06 generic (M: real: = 1.2 e-7; D: real: = 4.0 e-6;
   K: real: = 2.6455; eps: real: = 1.0006;
   epsVak: real: = 8.85419; Area: real: = 1.0 e-6;
   d: real: = 5.0 e-5; The Volt: real: = 10.0);
07 port (terminal Fin: mechanical);
08 end entity DAVACH_ACCEL_CAPAS_Fe;
09 architecture of archDAVACH_ACCEL_CAPAS_
   _Fe DAVACH_ACCEL_CAPAS_Fe is
10 constant Kon: real: = 0.5-e;
11 quantity x: real: = 0.0;
12 quantity R: real: = 0.0;
13 quantity V: real: = 0.0;
14 quantity F across the Fin to GROUND;
15 quantity C: real: = 0.0;
16 quantity Q: real: = 0.0;
17 quantity: real: = 0.0;
18 quantity of Fe: real: = 0.0;
19 begin
20 V'dot = (F + Fe-R)/M;
21 Fe = Kon * Area * eps * epsVak * Volt * Volt/((d-x) * (d-x));
22 R = D * V + K * x;
23 x'dot = V;
24 C = eps * Area * epsVak/(d-x);
25 Q = C * Volt;
26 Q'dot = I;
27 end architecture archDAVACH_ACCEL_CAPAS_Fe;
```

Figure 7. The example of the VHDL-AMS model for electrostatic accelerometer with lamellar construction

The given VHDL-AMS model includes the following elements: the line 01-04 – included in the pattern library; 05 – the description of the global model parameters; 06 – ports description; 10-18-local options; 20-26 –description of the model's functioning, which takes into account the formula (1-3). In the 20th line accelerating is determined; in the 21st line the magnitude of the electronic power is evaluated; in the 23th – offset; in the 24th – capacity change; 25th – charge change, and the 26th line has the equation for the determination output current changes.

The VHDL-AMS capacitive accelerometer model of the counter-pivotal basic construction is shown in Fig. 8. The developed model includes a number of such basic blocks: description of the used libraries and units (lines 01-04); initialization of the global parameters (line 06); description of the incoming and output ports (line 7); local model parameters initialization (lines 10-19); the block describing models functioning (21-29). The line 23th defines displacement; 24th, 27th – capacity changes; 25th, 27th – charges change in C_1 and C_2 capacitors; 26th and 29th – output currents changes.

```
library Disciplines;
use the Tutorial. extra_functions all;
use Disciplines. electrical_system all;
use Disciplines. mechanical_system all;
ACCEL_COMB entity is
generic (M: real: = 1.2 e-7; D: real: = 4.0 e-6;
   K: real: = 2.6455; eps: real: = 1.0006;
   epsVak: real: = 8.85419; Area: real: = 1.0 e-6;
   d: real: = 5.0 e-5; Volt: real: = 10.0);
port (terminal Fin: mechanical);
end entity ACCEL_COMB;
archACCEL_COMB ACCEL_COMB architecture of is
quantity x: real: = 0.0;
quantity R: real: = 0.0;
quantity V: real: = 0.0;
quantity F across the Fin to GROUND;
quantity C1: real: = 0.0; quantity
Q1: real: = 0.0;
quantity I1: real: = 0.0;
quantity C2: real: = 0.0;
quantity Q2: real: = 0.0; quantity
I2: real: = 0.0;
begin
V'dot = (F-R)/M;
R = D * V + K * x;
x'dot = V;
C1 = eps * Area * epsVak/(d-x);
Q1 = C1 * Volt;
Q1 ' dot = I1;
C2 = eps * Area * epsVak/(d + x);
Q2 = C2 * Volt;
Q2 ' dot = I2;
end architecture archACCEL_COMB;
```

Figure 8. An example of a part of the VHDL-AMS for electrostatic accelerometer models based on counter-pivotal construction

The results of capacitive accelerometers basic models investigation. Thus, the developed VHDL AMS models are used at the circuit level of the automated MEMS design. In particular, the results of lamellar capacitive accelerometer analysis are shown in the Fig. 9. The input model parameter is the acceleration that changes its value from 100 to 100 m/c^2 (Fig. 9,*b*) and in accordance with the developed VHDL-AMS model, the generated power forces of the inertial power perform vibrational displacements (Fig. 9,*c*). The examples of the output capacity, charge and current changes are shown in the Fig. 9,*e-f*, respectively.

The obtained data allows to argue that due to the fact that capacity changes for such devices are within pF (picofarad), and current – tens and hundreds of nA, thus implementation of the output signal processing by the capacitive microphone requires applying the scheme with high sensitivity to current [14].

On the other hand the output parameters of the basic capacitive microsensor can be controlled with the help of constructive and technological parameters. Thus the increase in capacity is directly associated with the integral capacitor plates area, which, on the other hand, leads to the decrease in the number of items on a single semiconductor MEMS plate. Therefore, during the development of such devices with specified parameters multicriterion optimization problem should be solved.

The results of the counter-pivotal accelerometer analysis are shown in Fig. 10, Fig. 11 and Fig. 12. In particular, Fig. 10,*a* shows the example of the rectangular impact forces on the accelerometer signal and Fig. 10,*b* shows the generated acceleration change and shifting (Fig. 10,*c*).

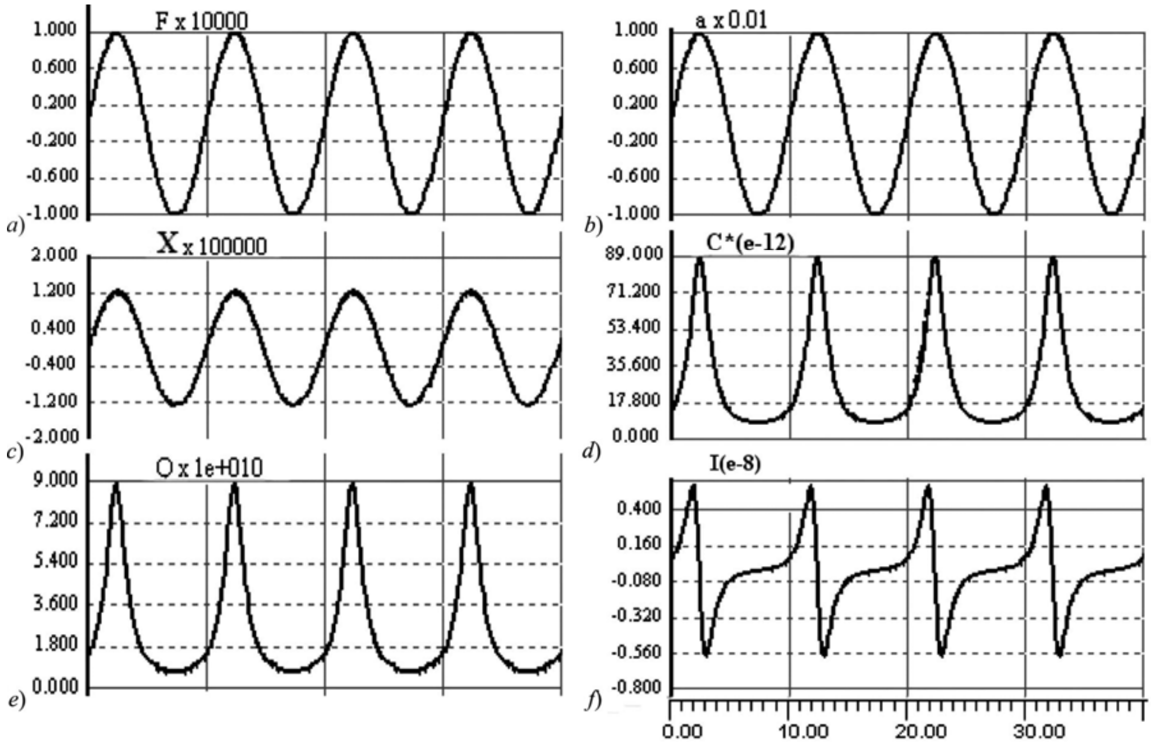

Figure 9. An example of the force magnitude changes (*N*) in time (*a*), of the acceleration changes in time under the applied force (*b*), of the shift changes (μm) (*c*), capacity (*pF*) (*d*), charge (*e*) and of the current changes (*A*) (*f*) in time due to acceleration

The Applied force generates changes in volume (Fig. 11,*a* and Fig. 11,*b*) and currents (Fig. 12,*a* and Fig. 12,*b*).

The analysis of the received data for counter-pivotal design capacitive accelerometer allows to argue that the generated currents depend on the C_1 and C_2 capacitors squares. Therefore, in the process of integrated capacitive accelerometers computer-aided design the surface area and the number of stubs should be increased. In addition, small values and output currents changes stipulate development and usage of the special electrical schemes [1].

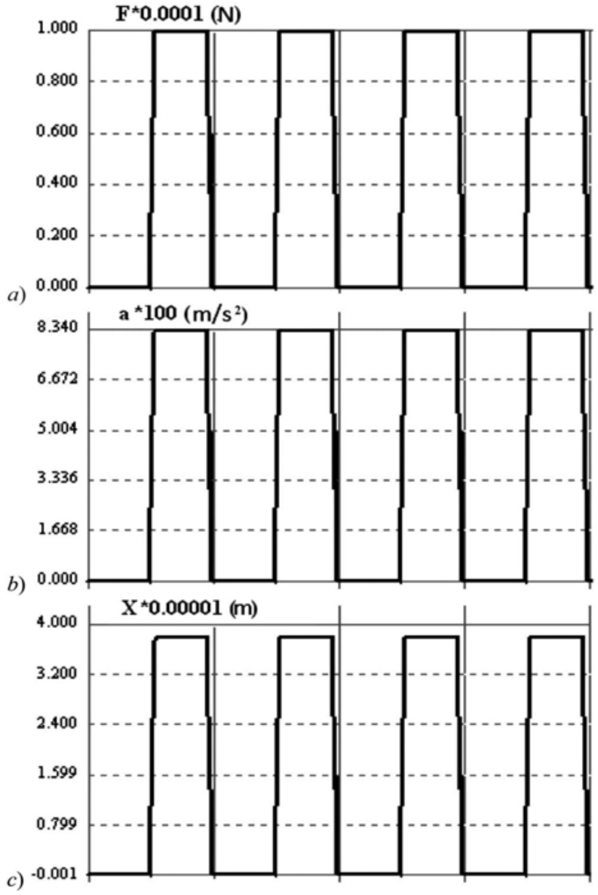

Figure 10. An example of the force applied to the accelerometer changes in time (*a*), of the acceleration changes in time due to applied forces (*b*) and of the shift changes in time due to acceleration (*c*)

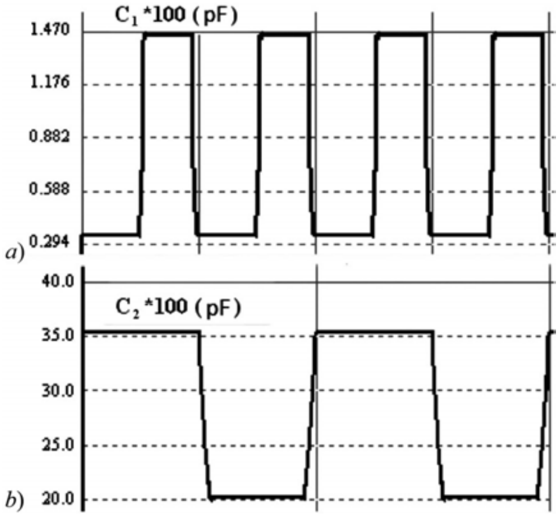

Figure 11. An example of the C_1 (*a*) and C_2 (*b*) capacity changes in time due to acceleration

Conclusions

1. The method of automated design of MEMS base elements of VHDL-AMS models for circuit design level, based on the electrical analogies method, ordinary differential equations systems and equations in partial derivatives has been developed. The sequence and number of the used differential equations is determined by the physical principles of MEMS element and the number of power transformations and allows to increase the level of the automation of VHDL-AMS models synthesis operations in comparison with the existing ones.

2. The basic VHDL-AMS model for the integrated capacitive lamellar sensor at the circuit level of development has been built. This enables to conduct research and analysis of the MEMS element output settings.

3. The basic VHDL-AMS model for the integrated capacitive counter-pivotal sensor at the circuit level of development has been built. This enables to conduct research and analysis of its parameters and investigate the output electric parameters dependence on the input mechanical ones.

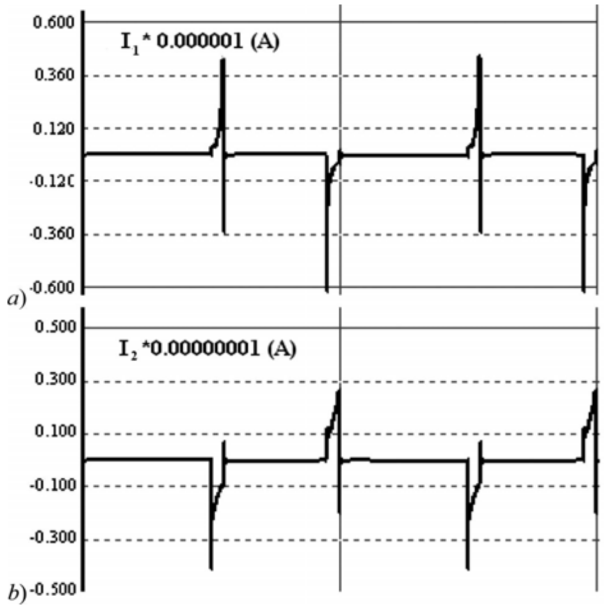

Figure 12. An example of the I_1 (*a*) and I_2 (*b*) current changes in time due to acceleration

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РОЗРОБЛЕННЯ БАЗОВИХ МОДЕЛЕЙ ЄМНІСНИХ АКСЕЛЕРОМЕТРІВ МОВОЮ VHDL-AMS ДЛЯ СХЕМОТЕХНІЧНОГО РІВНЯ АВТОМАТИЗОВАНОГО ПРОЕКТУВАННЯ

Розроблено базові моделі ємнісних МЕМС акселерометрів з використанням мови VHDL-AMS для схемотехнічного рівня автоматизованого проектування. Базові моделі розроблені для двох базових типів ємнісних акселерометрів: пластинчастої та гребінчастої інтегральних конструкцій. Розроблені моделі дають змогу визначати параметри вихідної напруги електричних ємнісних акселерометрів залежно від вхідних механічних та конструктивних параметрів та можуть бути використані для автоматизованого проектування МЕМС на схемотехнічному рівні. Окрім цього, наведено результати дослідження базових конструкцій пластинчастих та гребінчастих ємнісних акселерометрів. Описано розроблений метод автоматизованого проектування базових елементів МЕМС VHDL-AMS моделей для схемотехнічного рівня проектування, який ґрунтується на методі електричних аналогій та використовує системи звичайних диференціальних рівнянь і рівнянь у часткових похідних. Послідовність та кількість використаних диференціальних рівнянь визначається фізичними принципами функціонування елемента МЕМС та кількістю перетворень енергії, що дає змогу підвищити рівень автоматизації операцій синтезу порівняно з наявними методами. Синтезовано базова VHDL-AMS модель для інтегрального ємнісного акселерометра пластинчастої конструкції, яка дає змогу провести дослідження залежності вихідних параметрів від вхідних та провести аналіз налаштувань вихідних параметрів МЕМС елементів даного типу. Також побудовано базову VHDL-AMS модель для інтегрального ємнісного акселерометра гребінчастої конструкції, що дає змогу проводити дослідження в процесі автоматизованого проектування та провести аналіз його вихідних електричних параметрів від вхідних механічних.

Ключові слова: VHDL-AMS, САПР, схемотехнічний рівень проектування, ємнісні акселерометри, моделювання.

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