Accelerometers Production Technological Process Decomposition Parameters Model

Nevlydov Igor, Yevsieiev Vladyslav, Miliutina Svitlana, Bortnikova Viktoriia
Department of Technology and Automation of Radio Electronic and Computing Devices Production, Kharkiv National University of Radioelectronics, UKRAINE, Kharkiv, Nauki Ave, 14, E-mail: viktoriia.bortnikova@nure.ua, vladyslav.yevsieiev@nure.ua

Abstract - **In this paper the accelerometer production technological process parameters decomposition model is described.**

Keywords - **Accelerometer, MEMS, technological process, decomposition.**

I. INTRODUCTION

Current trends in the micro-electromechanical systems (MEMS) production require new approaches to improve the computer-aided design, which should satisfy the growing need for the development of effective technological processes (TP). In such conditions, existing approaches to the accelerometers production TP design automation should take into account the Industry 4.0 standards. However, the existing CAD systems do not allow to consider this and only automate one part of the TP [1]. The result is that today the task of accelerometers TP computer-aided design new methods developing is relevant.

To solve this problem it is necessary to develop a new basic parameters decomposition model that describe their relationships within the TP, which will allow to develop methods for computer-aided design accelerometers from the beginning to the end of the TP.

II. ACCELEROMETERS PRODUCTION TECHNOLOGICAL PROCESS DECOMPOSITION PARAMETERS MODEL

Let ψ – preform for accelerometer production, which is a substrate comprising the basic parameters (the substrate material, substrate thickness, substrate size, crystallographic orientation).

Therefore, basing on the TP theory we can present that the accelerometers production is a sequence that includes a plurality of production stages Q (substrate type selection, substrate preparation and so on), which are the technical process enlarged part: they are almost independent, are characterized by a logical completeness, spatial or temporal isolation. So, $Q=\{Q_1,Q_2,\ldots,Q_n\}$, where $n=1,2,3,\ldots,m$, for this research let's limit $m=11$ – the main famous stages, presented on fig.1.

The whole accelerometer production technological process may be represented as a process of transition from the preform ψ to the ready accelerometer Θ by performing a set of some stages sequences Q.

In the TP implementation of the preform ψ qualitative and quantitative characteristics are changed. The result is that in general each stage may be represented as an action sequence over ψ for end-product Θ getting.

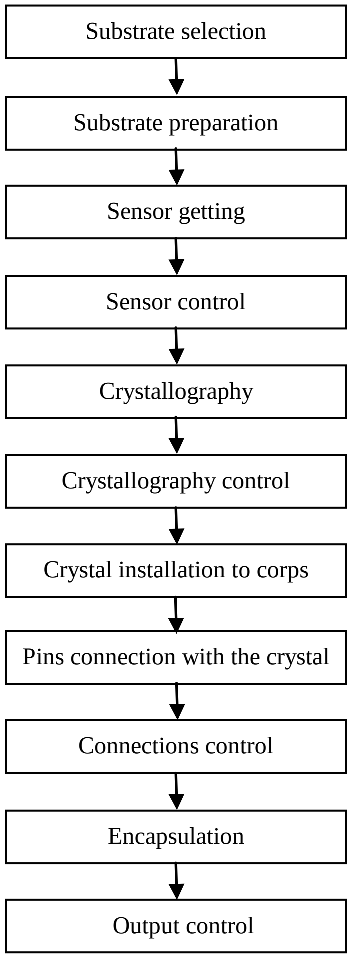

Fig.1 Accelerometers Production Main Stages Sequence

So, we can write an expression:

$$\psi \xrightarrow{Q} \Theta \tag{1}$$

Taking into account, that stages Q represent a sequence, we can expand expression 1 in such way:

$$\psi_0 \xrightarrow{Q_1} \psi_1 \xrightarrow{Q_2} \psi_2 \xrightarrow{Q_3} \psi_3 \xrightarrow{Q_4} \ldots \ldots \xrightarrow{Q_n} \psi_n \xrightarrow{Q_{n+1}} \Theta \tag{2}$$

So, a preform ψ represents a plurality of consecutive preform changes ψ_n, where $n=1,2,3,\ldots,m$ is an identifier of belonging to n stage Q_n.

In turn, each stage Q is divided into a number of technological operations O_p, that represent TP complete part, performed at one workplace.

Each operation O_p is one of the methods, used for one or another operation execution (e.g., «flip-chip» method, «anisotropic etching» method). Each stage Q is characterized by a different number of operations O_p, which is determined by this stage Q, depending on the parameters (sensitivity, measured acceleration range etc.), which should have a ready accelerometer Θ.

Then each stage Q_n contains a number of operations O_p to be performed in order to proceed to Q_{n+1} and represents the set of sequences to be performed for the accelerometer Θ.

Let's introduce the concept $\Rightarrow$ as an ordered sequence of each stage Q_n. So. We can represent Q as a plurality of interrelated operations sequence O^n_{pi}, where $n = 1,2,3,\ldots,m$ is an identifier that shows operations belong to a certain stage, and $i, j, k, l = 1,2,3,\ldots,m$ – is a operation O_p serial number at the stage Q_n. Plurality O^n_{pi} is an operations sequence, that are necessary and sufficient to be done to perform next stage Q_{n+1}.

Based on the above accelerometer production technological process presented in (2) can be represented in next way:

$$\begin{aligned}&(\{O^1_{p1} \to O^1_{p2} \to \ldots \to O^1_{pi}\} \in Q_1) \Rightarrow \\ &\Rightarrow (\{O^2_{p1} \to O^2_{p2} \to \ldots \to O^2_{pj}\} \in Q_2) \Rightarrow \ldots \\ &\ldots \Rightarrow (\{O^n_{p1} \to O^n_{p2} \to \ldots \to O^n_{pk}\} \in Q_n) = \Theta\end{aligned} \quad (3)$$

However, it is worth considering that in the TP construction (as shown in Fig. 1), there are stages Q, which do not change the preform ψ geometrical parameters, such as «substrate selection» stage (the definition of the material, size and substrate crystallographic orientation) and «control» stage, which are connected with the conduct of control after a certain stage (obtained sensor control, crystallography control, connections control, output control). Then, the stages Q, which will affect the geometric shapes, sizes and physicochemical properties of the preform ψ we'll call the main stages and denote them Q, and those operations that do not affect the change of the preform ψ geometric dimensions and ensure the uninterrupted flow of the main stages Q, we'll denote Q' and call secondary stages.

Existing TP analyses [2,3] showed, that the first stage Q_1 of accelerometer production technological process always is a «substrate selection», and the last stage is always a «output control» and both these stages do not affect the geometric dimensions change, then:

$$\psi_0 \xrightarrow{Q_1'} \psi_1, \text{ where } \psi_0 = \psi_1, \quad (4)$$

where Q_1' – the first stage of accelerometer production TP «substrate selection»; ψ_0 – an initial preform (substrate) before stage Q_1'; ψ_1 – a preform after stage Q_1'.

A preform ψ_0 is an initial preform (substrate), and a preform ψ_1 is a next preform after stage Q_1'. A preform ψ_0 after stage Q_1' is done has the same geometrical and physical properties as the preform ψ_1, because stage Q_1' doesn't change its не изменяет ее geometrical and physical properties, so, they are equal – $\psi_0 = \psi_1$. Therefore, in this research we assume that the presentation of the preform ψ_n which is obtained after stage Q_n', has an identifier ψ_n' that indicates that its geometry is not changed.

It should be noted that at the stages Q_n which modify the geometrical and physical parameters of the preform, $\psi_0 \neq \psi_1$. It can be concluded that the TP is an ordered sequence of transformations stages Q_n and Q_n' of the original preform to achieve ready accelerometer Θ.

Based on the above and expressions 2-4 let's write a preform ψ_0 changing stages sequence at an intermediate stage ψ_n, depending on the type of process:

$$\begin{aligned}&\psi_0 \xrightarrow{Q_1'} \psi_1' \xrightarrow{Q_2} \psi_2 \xrightarrow{Q_3} \ldots \\ &\ldots \xrightarrow{Q_n} \psi_n \xrightarrow{Q_{n+1}'} \Theta\end{aligned}, \quad (5)$$

Considering the expression 5 it can be concluded that if the stage is a stage Q_n' that $\psi_n' = \psi_{n+1}'$, and vice versa if Q_n, so, $\psi_n \neq \psi_{n+1}$.

On the basis of the proposed inequality it can be justified the presence of a stage Q_n' in a branch the TP construction. Stage Q_n' does not affect the ψ_n' geometrical and physical parameters, but it is an integral part of the TP. This justification will introduce and take into account control stages in the transition points of the graph and avoid getting the wrong accelerometer.

Theorem 1: About the stages existence Q_1'

The Theorem 1proof:

Let the stage Q_1' does not exist, then there is always $\psi_0 = \psi_1$, and accelerometer production technological process can be written in such way:

$$\begin{aligned}&\psi_0 \xrightarrow{Q_1} \psi_1 \xrightarrow{Q_2} \psi_2 \xrightarrow{Q_3} \ldots \\ &\ldots \xrightarrow{Q_n} \psi_n \xrightarrow{Q_{n+1}} \Theta \\ &\psi_0 = \psi_1 = \psi_2 = \psi_n = \ldots = \Theta\end{aligned}$$

However, if $\psi_0 \neq \psi_1$, then the entire the accelerometer production TP can be presented in next way:

$$\psi_0 \xrightarrow{Q_1} \psi_1 = 0$$
$$\psi_0 \neq \psi_1 = 0$$

As a result the TP on any part can be equal to zero, which makes it impossible to design the TP, and therefore rejects the assumption of the absence of stage Q_1'.

Based on the foregoing, the accelerometer production technological process can be represented as a graph, where the vertices are the iterations carried out on the preform ψ_n, and the edges are the ordered sequence of stages Q_n and $Q_n{}'$.

Then, the technological process sequence at stages 1-2 may be considered such that from the initial preform ψ_0 in a specific order of application stages $Q_1{}'$ and Q_2 we'll obtain a preform ψ_2, wherein the stage Q_1' is a stage that does not change the preform ψ_1' geometric dimensions, then:

$$\psi_0 \xrightarrow{Q_1'} \psi_1' \xrightarrow{Q_2} \psi_2 . \qquad (6)$$

This sequence should be presented as a graph, which has a closed cycle of variations for each stage Q_n.

Based on Theorem 1, on the stage Q_1', there are such options:

- if $\psi_0 = \psi_2$, then, there is no need to perform the stage Q_1' whereby $Q_1' = 0$;
- if $\psi_0 \neq \psi_2$, then, there is a need to execute stage Q_2.

At the stage Q_2 a preform ψ_1 must acquire all the necessary parameters inherent ψ_2, so, preform $\psi_1 \to \psi_2$ and the stage is performed until $\psi_1 = \psi_2$.

On Fig. 2 there is a graph reflecting stages Q_1' and Q_2 (in accordance with Fig. 1 – TP Stages 1 and 2) and the relationship with the state of the preform ψ_n after each stage Q_n.

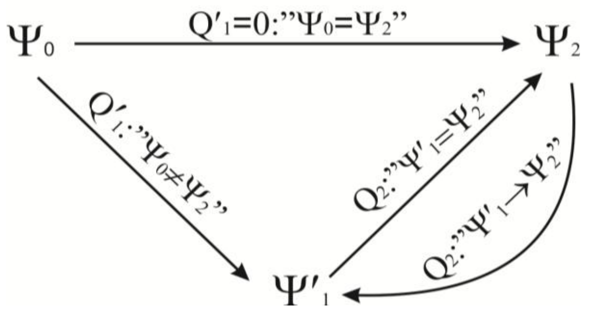

Fig.2 Accelerometer Production Technological Process at the Stages Q_1' and Q_2 Graph

Fig. 2 designates the condition, which is necessary to perform the next step Q_{n+1}:

:« *conditions value*».

Settling on Theorem 1 let's prove that there are operations O_{pi}^n that lead to changes in the preform ψ_n geometric parameters and belong to the stages Q_n - $O_{pi}^n \in Q_n$ and operations Q_n' that do not change the ψ_n' geometric parameters belong to the stages Q_n' – $O_{pi}'^n \in Q_n'$.

So, the technological process shown in the expression 3 can be written as:

$$\begin{aligned}&(\{O_{p1}'^1 \to O_{p2}'^1 \to \ldots \to O_{pi}'^1\} \in Q_1') \Rightarrow \\ &\Rightarrow (\{O_{p1}^2 \to O_{p2}^2 \to \ldots \to O_{pj}^2\} \in Q_2) \Rightarrow \ldots \\ &\ldots \Rightarrow (\{O_{p1}^n \to O_{p2}^n \to \ldots \to O_{pk}^n\} \in Q_n) \Rightarrow \\ &\Rightarrow (\{O_{p1}'^{n+1} \to O_{p2}'^{n+1} \to \ldots \to O_{pl}'^{n+1}\} \in Q_{n+1}') = \Theta\end{aligned} \qquad (7)$$

Then, based on the fig. 2 and expressions 6-7, for this research it must be considered an integral part of the TP as a transition, which is a part of a technological operation O_{pi}^n. Each operation O_{pi}^n includes a different number of transitions Ω.

The transition should be understood in next way: for any operation O_{pi}^n there is a transition Ω, which is a completed operation O_{pi}^n part, that is performed on one or more surfaces of the preform ψ_n by one or more tools working simultaneously without altering or automatic changing the working equipment modes.

For each operation $O_{pi}^n \in Q_n$ there is a main transition Ω, that affects the preform ψ_n geometry change, and for each operation $O_{pi}'^n \in Q_n'$, there is a secondary transition Ω' – a transition that does not cause changes in the preform ψ_n geometry, but it is necessary for main transition execution Ω.

Thus, the deformation of the preform ψ_n occurs during the main O_{pi}^n and secondary $O_{pi}'^n$ operations execution, as well as main Ω and secondary Ω' transitions.

In production conditions in any the TP we can identify options, and for each operation O_{pi}^n and determine the interaction of various factors: accelerometer and sensor design, chassis design, machining accuracy and crystallography, the physicochemical properties of the accelerometer, the material costs of the operation.

Then define the factors in the operation O_{pi}^n as $\dot{V}_i$ input parameters (characteristics of the initial preform

ψ_0 the and the preform ψ_{n-1}, before to i-th operation O_{pi}^{n} execution), the output $\hat{\mathrm{P}}_i$ (the preform ψ_n characteristics after i-th operation execution O_{pi}^{n}) and $\tilde{\mathrm{N}}_i$ variable technological parameters of the main Ω and secondary Ω' transfer for i-th O_{pi}^{n} operation and $O_{pi}'^{n}$ execution respectively, i.e. parameters of any transition Ω and Ω'.

Then parameters $\dot{V}_i$, $\hat{\mathrm{P}}_i$, $\tilde{\mathrm{N}}_i$, determine interaction factors for any operation O_{pi}^{n} and $O_{pi}'^{n}$, they are interlinked, they have complex interactions and trey are combined in sets. Thus, any operation O_{pi}^{n} and $O_{pi}'^{n}$ can be represented as a system of interaction between the input $\dot{V}_i$ variable parameters $\tilde{\mathrm{N}}_i$ and the output parameters $\hat{\mathrm{P}}_i$ of the operation O_{pi}^{n}.

The value of each parameter is within a certain range specified by the physical nature of this parameter or the TP requirements, so a constraints group associated with the parameters variation range, can be represented in the form of inequalities (8).

$$
\begin{aligned}
&\dot{V}_{i\min} \le \dot{V}_i \le \dot{V}_{i\max},\\
&\hat{\mathrm{P}}_{i\min} \le \hat{\mathrm{P}}_i \le \hat{\mathrm{P}}_{i\max},\\
&\tilde{\mathrm{N}}_{i\min} \le \tilde{\mathrm{N}}_i \le \tilde{\mathrm{N}}_{i\max}.
\end{aligned} \tag{8}
$$

Each of the parameter sets $\dot{V}_i$, $\hat{\mathrm{P}}_i$, $\tilde{\mathrm{N}}_i$ is characterized by a set of these parameters allowable values. Let's denote each element of sets $\dot{V}_i$, $\hat{\mathrm{P}}_i$, $\tilde{\mathrm{N}}_i$ as $\dot{v}_i$, $\hat{p}_i$, $\tilde{n}_i$, and define these sets in such way (9).

$$
\begin{aligned}
\dot{V}_i &= \left\{\dot{v}_i \middle| \dot{v}_{i\min} \le \dot{v}_i \le \dot{v}_{i\max} \middle| \right\} \dot{v}_i \subseteq \dot{V}_i,\\
\hat{\mathrm{P}}_i &= \left\{\hat{p}_i \middle| \hat{p}_{i\min} \le \hat{p}_i \le \hat{p}_{i\max} \middle| \right\} \hat{p}_i \subseteq \hat{\mathrm{P}}_i,\\
\tilde{\mathrm{N}}_i &= \left\{\tilde{n}_i \middle| \tilde{n}_{i\min} \le \tilde{n}_i \le \tilde{n}_{i\max} \middle| \tilde{n}_i \right\} \tilde{n}_i \subseteq \tilde{\mathrm{N}}_i.
\end{aligned} \tag{9}
$$

Expression (9) shows, each element of sets $\dot{V}_i$, $\hat{\mathrm{P}}_i$, $\tilde{\mathrm{N}}_i$ is an subset $\dot{v}_i$, $\hat{p}_i$, $\tilde{n}_i$, its elements are sets of limited values (min и max) within the values scope of this parameter.

The input parameters $\dot{V}_i$ for each operation O_{pi}^{n} are those parameters that are obtained after each operation O_{pi-1}^{n}, and output parameters $\hat{\mathrm{P}}_i$ are those parameters that are obtained after the operation O_{pi}^{n} and are necessary to execute the operation O_{pi+1}^{n}. Each operation O_{pi}^{n} contains a sequence of transitions Ω_i, and transitions Ω_i contain variables $\tilde{\mathrm{N}}_i$.

Let's represent the above in the form of interconnection that is shown in Fig. 4.

$$
O_{pi-1} \xrightarrow{\dot{V}_{pi}} \underbrace{\left[\Omega_{i-1} \to \Omega_i \to \Omega_{i+1} \ldots \to \Omega_{i+n}\right]}_{O_{pi}} \xrightarrow{\hat{\mathrm{P}}_{pi}} O_{pi+1}
$$

Fig.4 Parameters $\dot{V}_i$, $\hat{\mathrm{P}}_i$, $\tilde{\mathrm{N}}_i$ and transitions Ω_i interconnection for each operation O_{pi}^{n}

However, options are not confined only to operations O_{pi}^{n}, but also for all the stages Q_n there are input $\dot{V}_i$ and output parameters $\hat{\mathrm{P}}_i$ `. These parameters will have an identifier ψ_n and they are necessary in order to be able to evaluate and verify matching the preform ψ_n parameters after each stage Q_n. So, we can represent (7) in such way (10).

$$
\begin{aligned}
&\psi_0 \overset{\dot{V}_{\psi_0}}{\Longrightarrow} \left(\left\{\left\{\left\{\tilde{N}_i\right\} \in \Omega_i'\right\} \in O_{p1}'^{1} \xrightarrow{\hat{P}_{p1} = \dot{V}_{p2}} \left\{\left\{\tilde{N}_i\right\} \in \Omega_i'\right\} \in\right.\right.\\
&\left.\left.\in O_{p2}'^{1} \xrightarrow{\hat{P}_{p2} = \dot{V}_{p3}} \ldots \xrightarrow{\dot{V}_{pi-1}} \left\{\left\{\tilde{N}_i\right\} \in \Omega_i'\right\} \in O'^{1}_{pi}\right\} \in Q_1'\right) \overset{\hat{P}_{\psi_1'}}{\Longrightarrow}\\
&\overset{\hat{P}_{\psi_1'}}{\Longrightarrow} \psi_1' \overset{\dot{V}_{\psi_2'}}{\Longrightarrow} \left(\left\{\left\{\left\{\tilde{N}_i\right\} \in \Omega_i\right\} \in O_{p1}^{2} \xrightarrow{\hat{P}_{p1} = \dot{V}_{p2}} \left\{\left\{\tilde{N}_i\right\} \in \Omega_i\right\} \in\right.\right.\\
&\left.\left.\in O_{p2}^{2} \xrightarrow{\hat{P}_{p2} = \dot{V}_{p3}} \ldots \left\{\left\{\tilde{N}_i\right\} \in \Omega_i\right\} \in O_{pj}^{n}\right\} \in Q_2\right) \overset{\hat{P}_{\psi_2}}{\Longrightarrow} \psi_2 \overset{\dot{V}_{\psi_3}}{\Longrightarrow} \ldots \overset{\dot{V}_{\psi_{n-1}}}{\Longrightarrow}\\
&\overset{\dot{V}_{\psi_{n-1}}}{\Longrightarrow} \left(\left\{\left\{\left\{\tilde{N}_i\right\} \in \Omega_i\right\} \in O_{p1}^{n} \xrightarrow{\hat{P}_{p1} = \dot{V}_{p2}} \left\{\left\{\tilde{N}_i\right\} \in \Omega_i\right\} \in O_{p2}^{n} \xrightarrow{\hat{P}_{p2} = \dot{V}_{p3}} \ldots\right.\right.\\
&\left.\left.\ldots \xrightarrow{\dot{V}_{pi-1}} O_{pk}^{n} \in \left\{\Omega_i \in \left\{\tilde{N}_i\right\}\right\}\right\} \in Q_n\right) \overset{\dot{P}_{\psi_n}}{\Longrightarrow} \psi_n \overset{\dot{V}_{\psi_{n+1}}}{\Longrightarrow} \left(\left\{\left\{\left\{\Omega_i' \in \left\{\tilde{N}_i\right\}\right\}\right\} \in\right.\right.\\
&\in O_{p1}'^{n+1} \xrightarrow{\hat{P}_{p1} = \dot{V}_{p2}} \left\{\left\{\tilde{N}_i\right\} \in \Omega_i'\right\} \in O_{p2}'^{n+1} \xrightarrow{\hat{P}_{p2} = \dot{V}_{p3}} \ldots\\
&\left.\left.\ldots \xrightarrow{\dot{V}_{pi-1}} \left\{\left\{\tilde{N}_i\right\} \in \Omega_i'\right\} \in O_{p1}'^{n+1}\right\} \in Q_{n+1}'\right) \overset{\hat{P}_{\Theta}}{=} \Theta
\end{aligned} \tag{10}
$$

In (10) $\dot{V}_{\psi_0}$ represents initial parameters inherent the preform ψ_0. The output parameters $\hat{\mathrm{P}}_{p_i}$ obtained after the operation O_{pi}^{n} must conform to a predetermined range of input parameters $\dot{V}_{p_i+1}$ for the operation O_{pi+1}^{n}. Then and only then we can assume that the TP should be consistently developed in accordance with the sequence and does not have significant deviations in terms of the set allowable range of parameter values.

Expression (10) represents an ideal accelerometer production TP, when output $\hat{\mathrm{P}}_{p_i}$ and initial $\dot{V}_{p_i+1}$ parameters meet prescribed allowable range of values.

In order to take into account all the existing in real TP options let's write these particular cases, which are presented below.

The first option, when the output parameters $\hat{\mathrm{P}}_{p_i}$ obtained after an operation O_{pi}^{n}, correspond to the input parameters $\dot{V}_{p_i+1}$ for following operation O_{pi+1}^{n}:

$$\hat{\mathrm{P}}_{p_i} = \dot{V}_{p_i+1}$$

In this case, we can proceed to the next operation: O_{pi+1}^{n}.

The second variant, when the output parameters $\hat{P}_{p_i}$ are less than the maximum allowable values for the input parameters $\dot{V}_{p_i+1}$:

$$\hat{P}_{p_i} \neq \dot{V}_{p_i+1} \wedge \hat{P}_{p_i} > \dot{V}_{p_i+1\max},$$

In this case, you must return the preform ψ_n to the previous stage O_{pi}^{n} and modify it until the output parameters $\hat{P}_{p_i}$ do not match the input parameters $\dot{V}_{p_i+1}$.

The third variant, when the output parameters $\hat{P}_{p_i}$ are smaller than the minimum allowable values for the input parameters $\dot{V}_{p_i+1}$:

$$\hat{P}_{p_i} \neq \dot{V}_{p_i+1} \wedge \hat{P}_{p_i} < \dot{V}_{p_i+1min} \vee (reject) \vee (another\_TP)$$

In this case, the preform ψ_n can't be modified in the previous stage O_{pi}^{n} and represents a defective product. However, the preform ψ_n may be used in another TP where it will meet the specified parameters ($\hat{P}_{p_i} = \dot{V}_{p_i+1}$).

Thus, the output parameters $\hat{P}_{p_1}$ do not always correspond to specify the correct values of the input parameters $\dot{V}_{p2_i}$, and therefore special cases two and three may exist, and that should prove.

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III. Conclusion

In paper accelerometers production technological process decomposition parameters model is proposed. It allows to simplify technological process design and avoid the creation of "false" paths in the build tree. This is implemented due to the each TP parameter decomposition.

The model takes into account not only the main stages, operations and transitions, but also the concept of an intermediate and auxiliary control. This will enable the implementation of control parameters in operations Q_n between stages O_{pi}^{n}. Thus, it will be possible to increase accelerometers production quality and reduce the percentage of defective products at finish. The model allows to identify defective products in TP building process and to modify their occurrence in the early stages. However, it will increase TP design time, but will significantly improve the quality and cost-effectiveness by monitoring the "weak" places in accelerometers production, thus providing a high competitive ability and increasing production economic characteristics.