Interval Non-linear Model of Information Signal Characteristics Distribution for Detection of Recurrent Laryngeal Nerve during Thyroid Surgery

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Abstract

The work provides an analysis of known methods and technical means of identifying and visualizing the recurrent laryngeal nerve during thyroid surgery. There's proposed a method of building a non-linear model for detecting the location of the laryngeal nerve in the area of thyroid surgery. It's based on the characteristics of the information signal from the preliminary stimulation of the tissues of the surgical wound with an alternating current of a fixed frequency and the subsequent construction of the distribution function of the response to stimulation. The proposed method simplifies the procedures for identifying of the interval model, in particular, due to the analytical representation of the objective function of the optimization problem of their identification, and, accordingly, reduces the time spent on building the non-linear models based on interval data. Based on real experimental data obtained during thyroid surgery an interval non-linear model was built, which enables detection and visualization of the location of the laryngeal nerve in the thyroid surgery area and, accordingly, reducing the risk damage of its.

Keywords 1

Thyroid surgery, recurrent laryngeal nerve, information signal amplitude, interval data, interval non-linear model, model identification, optimization problem

1. Introduction

The main problem when conducting thyroid surgery is the identification of the recurrent laryngeal nerve, the damage of which leads to the patient losing his voice, as well as to other negative consequences related to the functioning of the human respiratory system [1, 2]. As a rule, the means used during such surgery make it impossible to visualize the process of identifying the laryngeal nerve, also it are based on the dangerous procedure of introducing the patient to the third stage of anesthesia, where there is a high risk of transition to a state of clinical death [3, 4].

The process of visualizing the laryngeal nerve is extremely complex and includes the procedure for its detection [5, 6, 7]. The analysis of known technical means of detecting the recurrent laryngeal nerve during thyroid surgery made it possible to establish the general principle of their surgery, which is based on stimulation with a constant electric current in the area of surgery and evaluating the results of this s on the vocal cords If the area of stimulation includes the recurrent laryngeal nerve, the vocal cords are shortened, but if the stimulation is done on the muscle tissue, the reaction to the stimulation will be insignificant. The basis of the method of identification of the laryngeal nerve from other tissues of the area thyroid surgery than proposed by the authors [8, 9, 10] is to ensure the accuracy of detection and visualization of the location of the laryngeal nerve in the surgical wound. The task is solved by the fact that the tissue stimulation in the area thyroid surgery is carried out by an alternating current of a fixed frequency which provides a low conductivity of the electrical signal through the

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muscle tissues and a high conductivity of the electrical signal through the laryngeal nerve and muscles that control the tension of the vocal cords, followed by registration of the contraction of the vocal cords at a given frequency by a sound sensor installed in the breathing tube placed in the patient's larynx, followed by its conversion into an electrical signal, and the output information signal, which characterizes the proximity to the laryngeal nerve, is determined by the change in the amplitude of the electric current of a given frequency [8].

To visualize the location of the laryngeal nerve in the surgical wound, information signal processing tools are used [10]. A signal processing software module includes filtering the signal at the excitation frequency, determining the maximum amplitude of the filtered signal for each observation, and recording the received data in interval form, taking into account errors of various nature. Moreover, the measurement of the interval value of the information signal amplitude is carried out according to the coordinates on the thyroid surgery area, which are fixed on a sterile grid, respectively, placed on the wound.

In papers [9, 10], the authors have proposed methods for constructing an interval models that describe the maximum amplitude of the information signal depending on the coordinates on the surgical wound, based on tolerance and guaranteed interval or ellipsoidal estimates of the parameters of the algebraic expression. However, the computational complexity of implementing these methods complicates online-visualization of the location of the recurrent laryngeal nerve during thyroid surgery. Therefore, the actual task is to develop a method for identifying the model of the information signal characteristics distribution with minimal computational costs for visualizing the location of the laryngeal nerve in the thyroid surgery area.

2. Method for building an interval model of the distribution of information signal characteristics for the recurrent laryngeal nerve's detection in the thyroid surgery area

The process of building mathematical models includes solving two problems: structural and parametric identification [11]. At the same time, the task of identification the model structure is more difficult and primary, since it's necessary to first define the basic functions, generate the structure of the model, and then calculate parameter estimates for selecting the optimal or "best". The most effective methods of structural identification of interval models are based on self-adaptation and self-organization procedures by analogy with the behavioral models of a bee colony. Complex optimization problems are solved for this [12, 13, 14, 15].

The distribution of the information signal characteristics in the thyroid surgery area we'll be described by interval mathematical models in the form of a nonlinear algebraic expression. Then we'll search for the resulting information signal characteristic A_0 (maximum amplitude) in the non-linear algebraic expression form of following kind:

$$A_0(\lambda_s,\vec{D}) = \varphi_{m+1}^s\left(\vec{g}(\vec{D})\right)\varphi_1^s(\vec{D})+\ldots+\varphi_{2m}^s\left(\vec{g}(\vec{D})\right)\varphi_m^s(\vec{D}), \quad (1)$$

where $\lambda_s = \left\{\varphi_1^s(\vec{D}),\ldots,\varphi_m^s(\vec{D}),\varphi_{m+1}^s\left(\vec{g}(\vec{D})\right),\ldots,\varphi_{2m}^s\left(\vec{g}(\vec{D})\right)\right\}$ – is a set of unknown basis functions (of a known class), and the basis functions $\varphi_{m+1}\left(g_1(\vec{D})\right),\ldots,\varphi_{2m}\left(g_m(\vec{D})\right)$ relate to unknown model parameters $g_i, i = 1,\ldots,m$ and the result of experimental measurements obtained in interval form:

$$D_i,\cdots,D_i \to [A_i^-;A_i^+], i = 1,\ldots,N, \quad (2)$$

where N – is number of measurements.

Let's set the conditions for the consistency of the model with experimental interval data as it's customary in interval analysis:

$$A_0\left(\lambda_s,\vec{D}_i\right) \in [A_i^-;A_i^+], \forall i = 1,\ldots,N, \quad (3)$$

where $A_0\left(\lambda_s,\vec{D}_i\right)$ – means the true value of the information signal output characteristic for a fixed model structure λ_s and for fixed input variables' values $\vec{D}_i$.

Parameter values $g_1, \ldots, g_m$ of the model only remain unknown in this case. Taking into account conditions (3) and replacing $A_0(\lambda_s, \vec{D}_i)$ with expression (1) for fixed values of the input variables $\vec{D}_i$, we'll obtain the following system of interval non-linear algebraic equations (ISNAE):

$$\begin{cases} A_1^- \leq \varphi_{m+1}^s\left(\vec{g}(\vec{D}_1)\right)\varphi_1^s(\vec{D}_1) + \cdots + \varphi_{2m}^s\left(\vec{g}(\vec{D}_N)\right)\varphi_m^s((\vec{D}_1)) \leq A_1^+; \\ \vdots \\ A_N^- \leq \varphi_{m+1}^s\left(\vec{g}(\vec{D}_N)\right)\varphi_1^s(\vec{D}_N) + \cdots + \varphi_{2m}^s\left(\vec{g}(\vec{D}_N)\right)\varphi_m^s(\vec{D}_N) \leq A_N^+. \end{cases} \quad (4)$$

Thus, the general form of the parametric identification problem of the interval model of the information signal characteristics when it's distributed to the thyroid surgery area in the interval system of non-linear algebraic equations form has been obtained. As is known [11], the solutions of this system they're obtained as a result of the implementation of an iterative procedure at each iteration of its they calculate the function $\delta([\vec{g}^-; \vec{g}^+])$ "quality" of estimation of mathematical model parameters. Accordingly, there's the task of structural identification of the interval model of the distribution of information signal characteristics as a task of repeatedly solving the problems of parametric identification of this model.

Let's assume that the solution of ISNAE (4) is obtained in the form of value intervals of model parameter estimates $[\hat{g}_1^-; \hat{g}_1^+], \ldots, [\hat{g}_m^-; \hat{g}_m^+]$. Let's substitute the obtained interval estimates into expression (4) with the fixed values of the input variables $\vec{D}_i$ (at the points of the experiment). Because of these substitutions, we'll get estimates of the information signal output characteristic in the interval form:

$$[\hat{A}^-(\lambda_s, \vec{D}_i); \hat{A}^+(\lambda_s, \vec{D}_i)] = \varphi_{m+1}^s([\hat{g}_1^-(\vec{D}_i); \hat{g}_1^+(\vec{D}_i)])\varphi_1^s(\vec{D}_i) + \cdots + \varphi_{2m}^s([\hat{g}_m^-(\vec{D}_i); \hat{g}_m^+(\vec{D}_i)])\varphi_m^s(\vec{D}_i), i = 1, \ldots, N. \quad (5)$$

Thus, the compatibility of ISNAE (4) means that the intervals of the values $[\hat{A}^-(\lambda_s, \vec{D}_i); \hat{A}^+(\lambda_s, \vec{D}_i)]$ of the predictive characteristics of the information signal at the points of experimental measurements $\vec{D}_i$ including to the intervals $[A_i^-; A_i^+], i = 1, \ldots, N,$ obtained experimentally, that is, if the following conditions are satisfied:

$$[\hat{A}^-(\lambda_s, \vec{D}_i); \hat{A}^+(\lambda_s, \vec{D}_i)] \subset [A_i^-; A_i^+], i = 1, \ldots, N. \quad (6)$$

Stating the fact that the structural identification problem of interval models of an information signal characteristics is a problem of repeatedly solving parametric identification problems of this model, and therefore from a computational point of view, it is NP complete. The complexity of the problem related to the complexity of the objective function, which is given algorithmically, is discrete and does not have an analytical representation, therefore it complicates the calculation [11].

At the same time, in the vast majority of problems of both structural and parametric identification of mathematical models, the criterion of minimizing the mean square deviation is used. On the other hand-side, it's mostly sufficient to find at least one model even with the interval formulation of the problem in the sense of solving ISNAE (4). In this case, the interval model (5) will be able written in the following form:

$$\hat{A}(\lambda_s, \vec{D}_i) = \varphi_{m_s+1}^s\left(\hat{g}_1^s(\vec{D})\right)\varphi_1^s(\vec{D}) + \ldots + \varphi_{2m_s}^s\left(\hat{g}_{m_s}^s(\vec{D})\right)\varphi_{m_s}^s(\vec{D}). \quad (7)$$

The task of identifying the interval model of the information signal characteristic distribution in the area of surgery we'll formulate in the optimization problem form:

$$\Delta(\lambda_s, \vec{g}^s(\vec{D}), \alpha_i) \xrightarrow{\lambda_s, \vec{g}^s(\vec{D}), \hat{\alpha}_i} min, \quad (8)$$
$$\lambda_s = \left\{\varphi_1(\vec{D}), \ldots, \varphi_{m_s}(\vec{D}), \varphi_{m_s+1}\left(\vec{g}(\vec{D})\right), \ldots, \varphi_{2m_s}\left(\vec{g}(\vec{D})\right)\right\} \in F,$$
$$\hat{g}_j^s \subset \left[g_j^{low}; g_j^{up}\right], j = 1, \ldots, m_s,$$
$$\hat{\alpha}_i \in [0, 1], i = 1, \ldots, N,$$

where

$$\Delta(\lambda_s, g_l^s, \alpha_i) = \sum_{i=1}^{N}\begin{pmatrix} \varphi_{m_s+1}^s\left(\hat{g}_1^s(\vec{D})\right)\varphi_1^s(\vec{D}) + \ldots + \varphi_{2m_s}^s\left(\hat{g}_{m_s}^s(\vec{D})\right)\varphi_{m_s}^s(\vec{D}) \\ -(\hat{\alpha}_i \cdot A_i^- + (1 - \hat{\alpha}_i \cdot A_i^+)) \end{pmatrix}^2 \quad (9)$$

where $F = \left\{\varphi_1(\vec{D}),\ldots,\varphi_M(\vec{D}),\varphi_{M+1}\left(\vec{g}(\vec{D})\right),\ldots,\varphi_{2M}\left(\vec{g}(\vec{D})\right)\right\}$ – is set of potential model's structural elements; $\hat{g}_1^s(\vec{D}),\ldots,\hat{g}_{m_s}^s(\vec{D})$ – is the parameters vector components of the *s*th model; g_j^{low}, g_j^{up} – is set minimum and maximum value for each model's parameter; m_s – is the parameters number of the interval model.

There's what the smaller value $\Delta\left(\lambda_s,\vec{g}_s(\vec{D}),\alpha_i\right)$ that the "better" structure of the interval model. If the equality is fulfilled

$$\Delta\left(\lambda_s,\vec{g}_s(\vec{D}),\alpha_i\right) = 0 \tag{10}$$

then the structure is guaranteed to allow building an adequate interval model of the information signal characteristic distribution, since the existence of the ISNAE (4) solution means that the condition (6) is satisfied, which in this case will have the following form:

$$\hat{A}\left(\lambda_s,\vec{D}_i\right) \in [A_i^-;\, A_i^+], i = 1,\ldots,N, \tag{11}$$

and it's equivalent condition

$$\hat{A}\left(\lambda_s,\vec{D}_i\right) = \alpha_i \cdot A_i^- + (1-\alpha_i \cdot A_i^+), \alpha_i \in [0,1], i = 1,\ldots,N, \tag{12}$$

since expression (12) is always a linear combination of limits of experimental values at measurement points $[A_i^-;\, A_i^+], i = 1,\ldots,N$.

The advantage of using the objective function in the form (9) is that it's in an analytical form and quadratic at least relative to the coefficients $\alpha_i \in [0, 1]$, $i = 1,\ldots,N$.

Thus, the task of model's parametric identification for a fixed structure is the search for the optimization problem solution:

$$\begin{gathered}\Delta\left(\lambda_s,\vec{g}_j^s(\vec{D}),\alpha_i\right) \xrightarrow{\vec{g}_j^s(\vec{D}),\hat{\alpha}_i} min,\\ \hat{g}_j^s(\vec{D}) \subset \left[g_j^{low}; g_j^{up}\right], j = 1,\ldots,m_s,\\ \hat{\alpha}_i \in [0, 1], i = 1,\ldots,N.\end{gathered} \tag{13}$$

To calculate the parameters of the interval model based on the optimization problem (13) and the given structure should be used nonlinear optimization methods, such as the Gradient Descent method, the Newton method or a combination of theirs [17, 18, 19]. The implementation of structural identification consists in selecting the structure of the interval model by reducing or increasing structural elements [20].

3. The interval non-linear model of the information signal characteristics distribution for the detection of the recurrent laryngeal nerve during thyroid surgery.

There were carried out the construction of an interval non-linear model of the characteristics of the information signal distribution in the area thyroid surgery based on the developed method. Experimental measurements on a sterile grid in the area of surgical intervention we've carried out based on of two coordinates:

$$D_i = \binom{x_i}{y_i}, i = 1, \ldots, 36. \tag{14}$$

The data were obtained in interval form based on information signal processing taking into account measurement errors and noises are presented in Table 1.

Detailed analysis of the data in the Table 1 showed that the structure of an adequate model of the maximum amplitudes of the information signal distribution in the thyroid surgery area should be to search with the inclusion of trigonometric basic functions. To reduce the number of such structural elements we've added for the parameters in the power function form $\varphi(\vec{g}) = sin^g(D)$.

Accordingly, a set of potential structural elements we've formed in this form:

$$F = \left\{1, x, y, xy, x^2, y^2, sin^g\left(\frac{\pi}{36}x\right), sin^g\left(\frac{\pi}{36}y\right), sin^g\left(\frac{\pi}{36}xy\right)\right\}. \tag{15}$$

In the process of selecting and increasing the model structure with elements from the set *F*, we've obtained a model structure based on the convolution of the following form:

$$\lambda_s = \left\{1, y, sin^g\left(\frac{\pi}{36}xy\right)\right\}. \quad (16)$$

Since the value of the objective function of the optimization problem (13) for this model's structure is close to zero (please, check Figure 1) and the condition (12) is satisfied, therefore, we obtained the optimal solution based on it.

Table 1

Results of experimental measurements of information signal characteristics

Measurement number	Measurement coordinates, D_i		Interval value of the maximum signal amplitude	
i	x_i	y_i	$[A_i^-; A_i^+]$	
1	1	1	8,0974	11,5326
2	1	2	9,5576	13,6124
3	1	3	13,0391	18,5709
4	1	4	15,2955	21,7845
5	1	5	19,8619	28,2881
6	1	6	25,6492	36,5308
7	2	1	9,0626	12,9074
8	2	2	14,421	20,539
9	2	3	21,7099	30,9201
10	2	4	28,5656	40,6844
11	2	5	33,8498	48,2103
12	2	6	43,032	61,288
13	3	1	10,1516	14,4584
14	3	2	18,1335	25,8265
15	3	3	31,5892	44,9907
16	3	4	37,8716	53,9384
17	3	5	47,8912	68,2087
18	3	6	50,7004	72,2096
19	4	1	13,1134	18,6766
20	4	2	23,3475	33,2525
21	4	3	43,1516	61,4584
22	4	4	47,4375	67,5625
23	4	5	49,5001	70,4985
24	4	6	43,3125	61,6875
25	5	1	13,2021	18,8001
26	5	2	32,1750	45,825
27	5	3	43,3125	61,6875
28	5	4	47,0250	66,975
29	5	5	44,5501	63,4495
30	5	6	26,8125	38,1875
31	6	1	16,5001	23,4996
32	6	2	37,5375	53,4625
33	6	3	46,4063	66,0938
34	6	4	42,0750	59,925
35	6	5	24,3375	34,6625
36	6	6	16,9125	24,0875

Based on calculated parameter estimates $\vec{g} = (7{,}7623 \quad 2{,}0482 \quad 45{,}2431 \quad 2{,}1703)$ the model of the information signal amplitude distribution on the thyroid surgery area in this form was constructed:

$$\hat{A}(\vec{D_i}) = 7{,}7623 + 2{,}0482y + 45{,}2431 sin^{2{,}1703}\left(\frac{\pi}{36}xy\right). \quad (17)$$

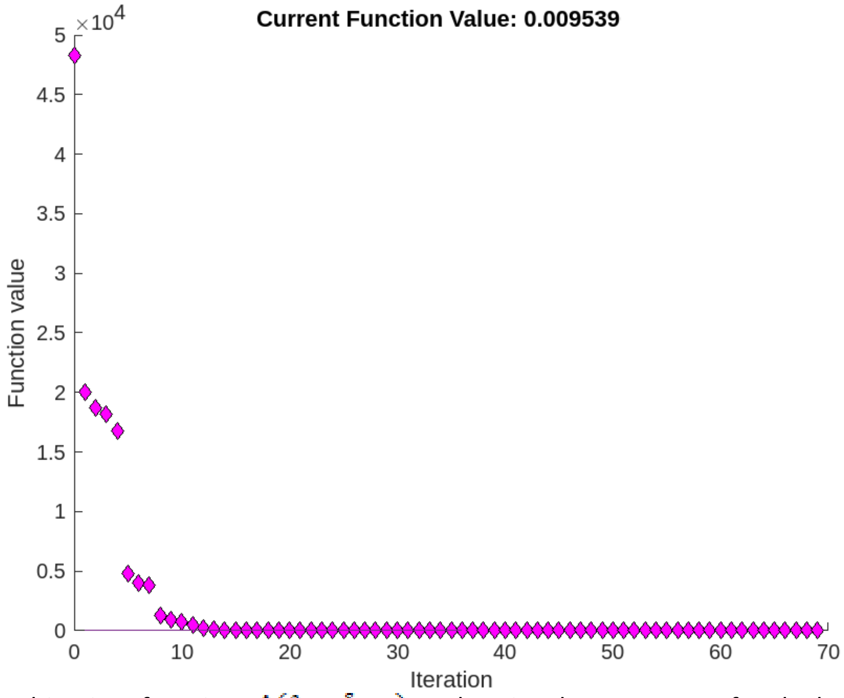


Figure 1: The objective function $\Delta(\lambda_s, g_j^s, \alpha_i)$ value in the process of calculating parameter estimates $\vec{g}$ and coefficients $\hat{\alpha}_i$ for the resulting model

There're given the predictive values $\hat{A}(\vec{D}_i)$ of the information signal amplitude that it's obtained based on the constructed model and, accordingly, calculated coefficients $\hat{\alpha}_i$ in process solving optimization problem (13) for parameter estimates of the resulting model in Table 2.

Table 2

The results of the interval model constructing of the maximum information signal amplitude distribution

Measurement number, i	Predictive amplitude value, $\hat{A}(\vec{D}_i)$	Coefficient estimates, $\hat{\alpha}_i$	Measurement number, i	Predictive amplitude value, $\hat{A}(\vec{D}_i)$	Coefficient estimates, $\hat{\alpha}_i$
1	10,0373	0,4354	19	14,2191	0,41
2	12,8713	0,1975	20	29,1968	0,7892
3	16,3145	0,4089	21	47,0182	0,3897
4	20,3638	0,2261	22	59,7198	0,4161
5	24,9817	0,3916	23	61,7681	0,464
6	30,1031	0,5902	24	53,1629	0,3642
7	10,823	0,5447	25	16,7887	0,3171
8	16,2673	0,6984	26	37,2303	0,3632
9	23,9583	0,7539	27	55,8709	0,8519
10	33,2932	0,609	28	59,7198	0,7099
11	43,3751	0,3362	29	47,348	0,5194
12	53,1629	0,4447	30	30,1031	0,5332
13	12,218	0,5094	31	19,8618	0,353
14	21,9101	0,7275	32	44,9699	0,6086
15	35,2319	0,3041	33	59,1501	0,6397
16	49,0664	0,4059	34	49,0664	0,5615
17	59,9674	0,3207	35	28,0548	0,3171
18	65,2948	0,7971	36	20,0517	0,3632

Figure 2 shows the graphs of the experimental interval corridor of the information signal amplitude and the predictive values that are obtained based on the model. The presented graphs demonstrate the inclusion of predictive values in the experimental corridor at each measurement point that satisfy condition (11) and indicates the adequacy of the constructed model.

So, constructed the interval non-linear model based on of real experimental data that were obtained during thyroid surgery will be able used to detect the placement of the laryngeal nerve in the thyroid surgery area and, accordingly, reduce the risk damage of its. Figure 3 shows the 2- and 3-dimensional visualization of the maximum amplitude distribution over the surgical area, which demonstrates the possible placement of the laryngeal nerve.

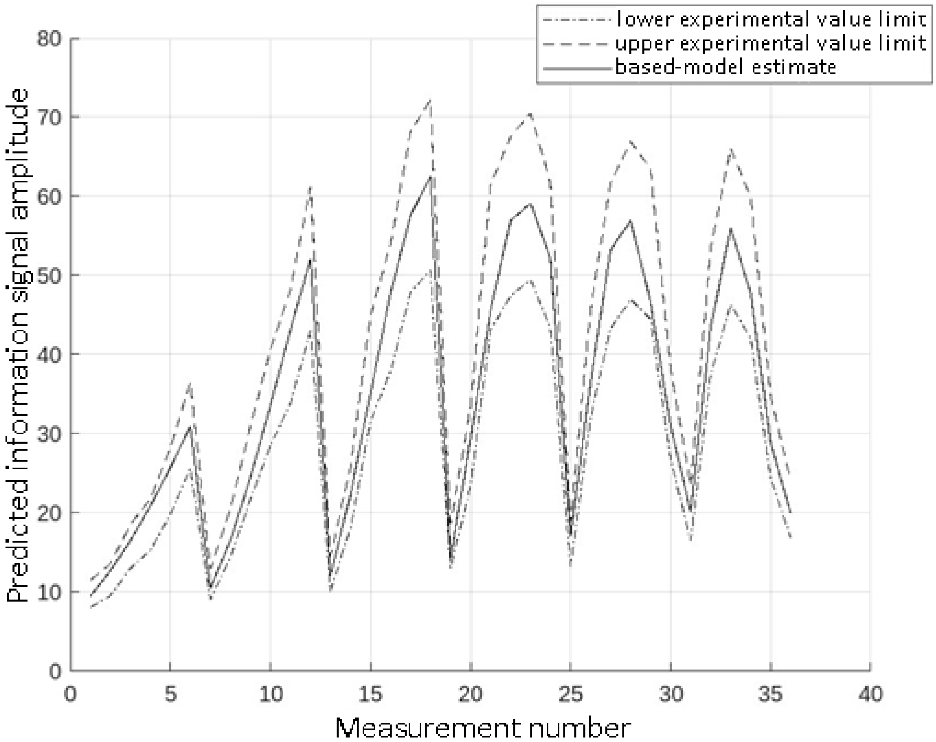


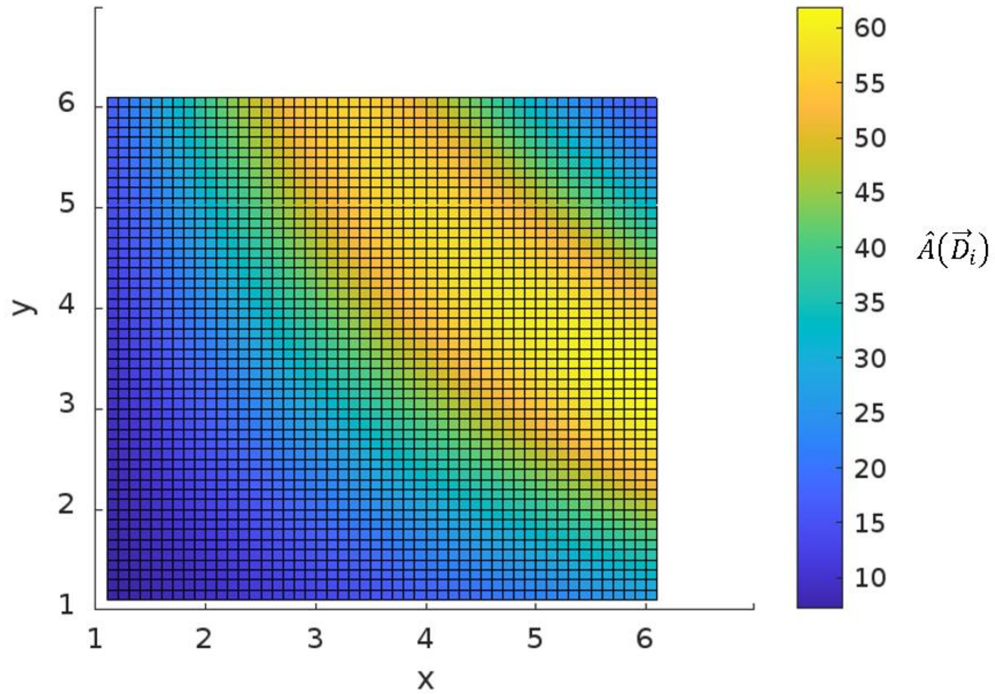
Figure 2: Interval values of experimental measurements and model-based predictive values of the information signal amplitude

4. Conclusions

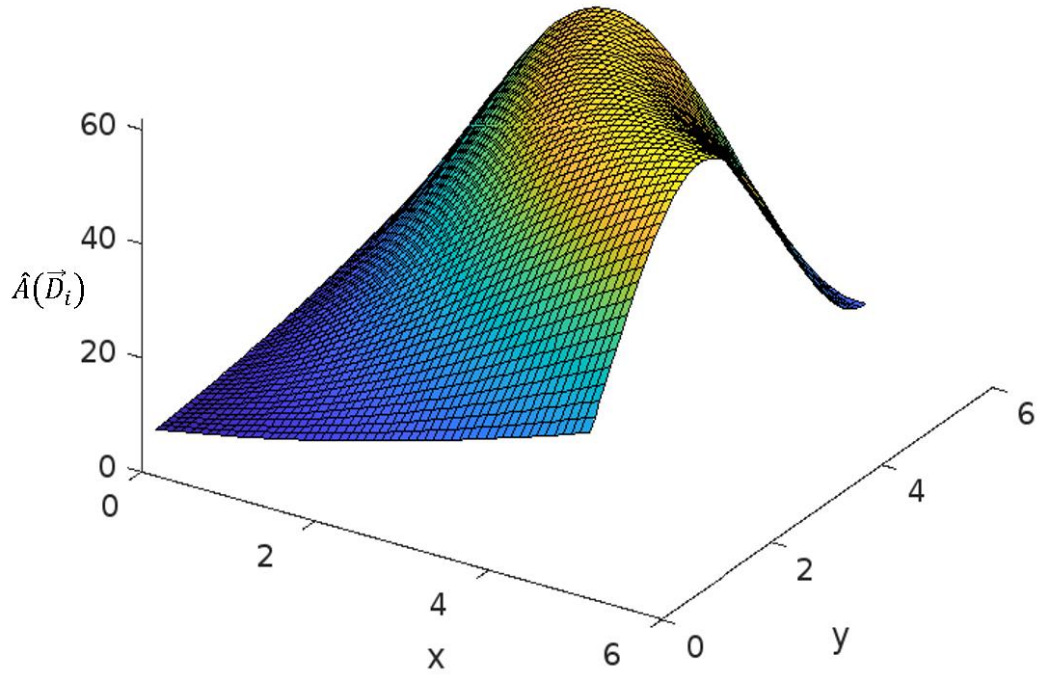
There were proposed based on the known method and technical means of the recurrent laryngeal nerve detecting during thyroid surgery the method and the non-linear model for predicting the information signal characteristics in order to detect the laryngeal nerve.

The method of building the non-linear models was created to detect the laryngeal nerve location in the area of surgical intervention based on the characteristics of the information signal. Signal was gotten from the previous excitation of the tissues of the surgical wound with an alternating current of a fixed frequency and the subsequent construction of the distribution function of the response to excitation. The proposed method simplifies and, accordingly, reduces the time spent on building a non-linear model based on interval data, in particular, due to the analytical representation of the objective function of the optimization problem of identification model.

Based on real experimental data of thyroid surgery the interval non-linear model was built it made possible to identify the placement of the laryngeal nerve in the thyroid surgery area, accordingly, reducing the risk damage of its.



a)



b)

Figure 3: Visualization of the information signal amplitude distribution based on the constructed model: a) two-dimensional image, b) 3d image.

5. References

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