Design of the Saturated Interval Experiment for the Task of Recurrent Laryngeal Nerve Identification

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Abstract: **the method of saturated design of experiment with interval data and its application for reccurent laryngeal nerve (RLN) location identification considered in this paper. Built saturated plan of experiment makes it possible to reduce the duration of surgery by reducing the number of points of irritation woven surgical wounds to identify locations RLN and reduce the risk of damage.**

Keywords: **neck surgery, recurrent laryngeal nerve, method of design if the saturated experiment, interval analysis, interval model.**

I. INTRODUCTION

RLN monitoring by using a special neuro monitors is very important procedure during the neck surgery. These monitors work based on the principle of surgical wound tissues stimulation and estimation of results of such stimulation [1-4]. However, the monitoring procedure does not guarantee a reduction in the risk of RLN damage, but only establishes the fact of its damage (not damage). In this case, the procedures for RLN identification are actual. In the paper [5] the task of visualizing the RLN location based on evaluation the maximal amplitude of signal as response to its stimulation by alternating current was considered. In paper [6] the method of constructing the difference schemes as a model for RLN location was considered. It should be noted that the informative parameter in both methods used maximum amplitude of the signal as response to stimulation of tissues in surgical wounds. The basis for localization the RLN damaging area assigned an interval model of distribution on surgical wound surface the maximum amplitudes of information signals. However, both methods require creation the uniform grid on surgical wound for tissues stimulation, which substantially increases the time of surgical operation. Note that in both cases the amount of tissue stimulation of the surgical wound is equal to the number of nodes in the grid. Such an approach greatly increases the time of the transaction by means of the procedure for RLN identification.

Based on the case of build a mathematical model, described in [5], in this article proposed to use an method of design experiment with a minimum number of experimental points (stimulation points) in order to reduce the accuracy of localization and at the same time ensure the highest possible accuracy of RLN localization. Such plans are called saturated I_G-optimal.

II. TASK STATEMENT

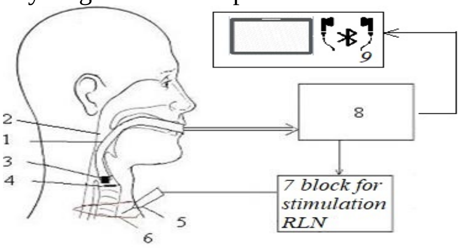
The stimulation of surgical wound tissues during the neck surgery based on electrophysiological method allows to identify the type of tissue with the purpose of RLN identification.

In articles [5-6] described the method for RLN identification among tissues of a surgical wound. The scheme of this method on the fig 1 are shown.

In respiratory tube 1 that inserted into larynx 2, the sound sensor 3 implemented and positioned above vocal cords 4.

Probe 5 is connected to stimulation block. It the functions as a current generator controlled by the single-board computer 8. Surgical wound tissues are stimulated by the block 7 via probe. As a result, vocal cords 4 are stretched.

Flow of air that passes through patient's larynx, is modulated by stretched vocal cords. The result is registered by voice sensor 3. Obtained signal is amplified and is processed by single-board computer 8.



1 is respiratory tube, 2 is larynx, 3 is sound sensor, 4 are vocal cords, 5 is probe, 6 is surgical wound, 7 is block for RLN stimulation, 8 is single-board computer, 9 is output part

Fig. 1. Method of RLN identification among tissues in surgical wound

The essence of processing the signal for a given simulation point is to determine its maximum amplitude and then to construct it the interval model of distribution on surgical wound surface the maximum amplitudes. The built model makes it possible to determine the risk-sensitive area in which the RLN is localized. To construct this model, it is necessary to minimize the number of stimulations of the tissues of the surgical wound. In the research [5-6] also found that the amplitude of the information signal depends on the distance from the stimulation point to the RLN. The near this point to the RLN, the greater the value of the amplitude of the information signal.

Before the surgery on the neck, the surgeon determines the area of the surgical intervention. Assume that in our case, this area is square, given by coordinates:

$$[x_1^- \le x_1 \le x_1^+; x_2^- \le x_2 \le x_2^+] \qquad (1)$$

where (x_1^-, x_2^-) - coordinates of lower limit rectangle surgery; (x_1^+, x_2^+) - coordinates of upper limit rectangle surgery.

Based on the results of works [5,6], we will assume that the values of the maximum amplitude of the information signal - the response to the irritation of the tissues of the surgical wound will be obtained in an interval form with a constant error $\Delta_i = \Delta, \forall i = 1,...,I$ for all stimulation points:

$$X = \begin{pmatrix} x_{11}, x_{12} \\ x_{21}, x_{22} \end{pmatrix}; \left[\vec{Y}\right] = \begin{pmatrix} \left[y_1^-; y_1^+\right] \\ \vdots \\ \left[y_i^-; y_i^+\right] \\ \vdots \\ \left[y_N^-; y_N^+\right] \end{pmatrix}, \quad (2)$$

where (x_{1i}, x_{2i}) - coordinates of stimulation points; $[y_i^-; y_i^+]$ - interval value of maximum amplitude of information signal for *i*-th stimulation point/

Lets consider the mathematical model for RLN identification in kind of algebraic equation described in [5]:

$$y_o = \beta_1 \cdot \varphi_1(\vec{x}) + ... + \beta_m \cdot \varphi_m(\vec{x}), \quad (3)$$

where $\vec{\beta} = (\beta_1, ..., \beta_m)^T$ is the vector of unknown parameters; $\vec{\varphi}^T(\vec{x}) = (\varphi_1(\vec{x}), ..., \varphi_m(\vec{x}))^T$ is the vector of known basic functions; $\vec{x} = (x_1, x_2)$ is vector of stimulation point coordinates; y_o is predicted value of maximal amplitude of information signal in point with coordinates *(x1, x2)*.

If for any *i*-th stimulation point the true unknown value of information signal amplitude is $y_{oi} = \vec{\varphi}^T(\vec{x}_i) \cdot \vec{\beta}$ belongs to the interval $[y_i^-, y_i^+]$, that is, we have the following condition:

$$y_i^- \le y_{oi} \le y_i^+, \; i=1,...,N \quad (4)$$

We get conditions:

$$\begin{cases} y_1^- \le b_1\varphi_1(\vec{x}_1) + \ldots + b_m\varphi_m(\vec{x}_1) \le y_1^+; \\ \vdots \\ y_N^- \le b_1\varphi_1(\vec{x}_N) + \ldots + b_m\varphi_m(\vec{x}_N) \le y_N^+. \end{cases} \quad (5)$$

System (5) is interval system of linear algebraic equations (ISLAE). The solution of this system will be obtained in the following form:

$$\vec{Y}^- \le F \cdot \vec{b} \le \vec{Y}^+, \quad (6)$$

where

$$F = \begin{pmatrix} \varphi_1(\vec{x}_1) \ldots \varphi_m(\vec{x}_1) \\ \vdots \\ \varphi_1(\vec{x}_N) \ldots \varphi_m(\vec{x}_N) \end{pmatrix}, \quad (7)$$

$\vec{Y}^- = \left\{y_i^-, i = 1, \ldots, N\right\}$, $\vec{Y}^+ = \left\{y_i^+, i = 1, \ldots, N\right\}$ – vectors composed of upper and lower bounds of intervals $[y_i^-, y_i^+]$, respectively; F – known matrix of values for basic functions, set by expression (7). If system (6) has solutions (or one solution), then the area of these solutions is denoted by Ω:

$$\Omega = \left\{\vec{b} \in R^m \mid \; \vec{Y}^- \le F \cdot \vec{b} \le \vec{Y}^+\right\}. \quad (8)$$

The set of all solutions Ω of ISLAE (6) makes it possible to determine the set of equivalent (in terms of the existing interval uncertainty) interval models of static systems belonging to the functional corridor:

$$[\hat{y}(x)] = [\hat{y}^-(x); \hat{y}^+(x)], \quad (9)$$

where

$$\hat{y}^-(\vec{x}) = \min_{\vec{b} \in \Omega} \left(\vec{\varphi}^T(\vec{x}) \cdot \vec{b}\right), \quad (10)$$

and

$$\hat{y}^+(\vec{x}) = \max_{\vec{b} \in \Omega} \left(\vec{\varphi}^T(\vec{x}) \cdot \vec{b}\right) \text{-} \quad (11)$$

lower and upper bounds of functional corridor, respectively.

The error of prediction of the interval model of the distribution of the maximum amplitude of the information signal will be evaluated in the following form [7-8]:

$$\Delta_{y(\vec{x})} = \max_{\vec{b} \in \Omega} \left(\vec{\varphi}^T(\vec{x}) \cdot \vec{b}\right) - \min_{\vec{b} \in \Omega} \left(\vec{\varphi}^T(\vec{x}) \cdot \vec{b}\right) \quad (12)$$

As you can see, the minimum number of stimulation points should be equal to the number of unknown *m* model parameters. Such experiments are called "saturated", the matrix *X* of the set (2) is a matrix of the plan, and the matrix *F* is an information matrix [7-8].

Thus, the purpose of this work is to find such a square matrix of a plan or an informational square matrix F_m of a saturated experiment that, at a known interval error $\Delta_i = \Delta, \forall i = 1,...m$, would provide the best of the predictive properties of the interval model of the distribution of the maximum amplitude of the information signal. This condition will ensure the highest precision localization RLN using this model.

III. Method of Design I_G-optimal Saturated Experiment

In the case of using a "saturated" block to estimate the parameters of interval model, its minimum prediction error in the input variable area $\vec{x} \in \chi$ is reached at one of the points of a given set of input variables $\vec{x}_j$ (j=1,...,m) [7-11]:

$$\Delta_{\min} = \min_{\vec{x}_j, j=1,..,m} \{\hat{y}^+(\vec{x}_j) - \hat{y}^-(\vec{x}_j)\} = \min_{j=1,..,m} \{2\Delta_j\} \quad (13)$$

$$\vec{x}^{\min} = \arg\min_{x_i, j=1,..,m} \{\hat{y}^+(\vec{x}_j) - \hat{y}^-(\vec{x}_j)\} \quad (14)$$

Procedures for calculating the maximum prediction error by interval models are much more complicated, even in the case of estimating its parameters based on the "saturated" block of ISLAE [7-11].

In work [8] expressions are given to calculate the error value at any point for the specified event:

$$\Delta_{y(\vec{x})} = 2 \cdot \sum_{j=1}^{m} \left|\alpha_j(\vec{x}) \cdot \Delta_j\right|, \vec{x} \in \chi \quad (15)$$

$$\vec{\alpha}^T(\vec{x}) = \vec{\varphi}^T(\vec{x}) \cdot F_m^{-1} \quad (16)$$

where $\alpha_j(\vec{x})$ – j-th component of vector $\vec{\alpha}(\vec{x})$, which in the general case depends on the choice of a point on the experiment area; $\Delta_j = 0,5 \cdot (y_j^+ - y_j^-)$ - interval errors in $\vec{x}_j$ observation points.

Based on the expressions (15), (16), we formulate a condition for choosing a "saturated" block to minimize the maximum prediction error in the area of the values of the input variables that determine the matrix *X* rows:

$$\max_{\vec{x}\in X}\left\{2\cdot\sum_{j=1}^{m}\left|\alpha_j(\vec{x})\cdot\Delta_j\right|\right\}\xrightarrow{F_m}\min, \quad . \qquad (17)$$
$$\vec{\alpha}^T(\vec{x})=\vec{\varphi}^T(\vec{x})\cdot F_m^{-1}$$

As you can see, the maximum value of prediction error in the area of input variables $\vec{x}\in X$ depends on the chosen "saturated" block. We will denote it: $\Delta_{\max}(F_m)$.

Expression (17) provides minimization of the maximum error of prediction of the interval model among all possible "saturated" blocks selected from ISLAE (5).

Let's make an analogy with the theory of design successive I_G-optimal interval experiment plans that minimize the maximum error of prediction of interval models [7-11]. In our case, the essence is: design some series of experiments with a small amount of observations (for example, a saturated experiment); get the corridor of interval models; analysis of the predictive properties of these models and on this basis the design of the next one observation [7-11].

Considering the requirements of providing optimal prognostic properties of the interval model (minimizing the maximum of prediction error) in the area of input variables, it is advisable to use this approach to select the "saturated" block from ISLAE (5) in order to simplify the task (17).

Note that in the procedure of I_G-optimal design on the first iteration, the "saturated" block is also chosen according to the I_G-criterion, the expression for which is represented (17). In our case, such iteration is meaningless due to high computational complexity. Therefore, in the first step of the method of estimating the set of values of the parameters of the interval models of static systems, the "saturated" block of ISLAE will be chosen arbitrarily.

Let the structure of the mathematical model of the static system be defined by the expression (3) with unknown parameters, given interval data (4) and ISLAE formed in the form (5).

Choose from ISLAE (5) an arbitrarily "saturated" block and compute its area of solutions, construct a prediction corridor with interval models in the form (9), where $\Delta_{\hat{y}(\vec{x})}$ are defined by expressions (15), (16).

By analogy with the procedure of successive I_G-optimal design, based on the expressions (15), (16), among (i=1,...,N) rows of the matrix X values of the input variables for which ISLAE (5) is composed, choose the vector-row $\vec{x}^{\max}$ for which we calculate the maximum prediction error, that is:

$$\vec{x}^{\max}=\arg\max_{\vec{x}_i=1,\dots,N}\left\{2\cdot\sum_{j=1}^{m}\left|\alpha_j(\vec{x}_i)\cdot\Delta_j\right|,\vec{x}_i, i=1,\dots,N\right\}, \qquad (18)$$
$$\vec{\alpha}^T(\vec{x}_i)=\vec{\varphi}^T(\vec{x}_i)\cdot F_m^{-1}$$

The vector obtained from expression (18) is a vector of values of input variables, which defines a certain interval equation in ISLAE (5). According to the procedure of successive I_G-optimal design, it is necessary to carry out the following measurement with respect to this vector-row.

Based on expression (14) to determine the vector of values of input variables, where the prediction error is minimal in the experiment area, we can state that if the vector $\vec{x}^{\max}$ coincides with the vector of values of input variables, for which one of the interval equations of the "saturated" block of ISLAE is constructed, then it would set the point with the minimum value of the prediction error. It is advisable to replace one of the interval equations in the ISLAE(5) by interval equation with the vector of values of the input variables $\vec{x}^{\max}$ defined by the expression (18) in the current "saturated" block. By analogy with the procedure of successive I_G-optimal design, we simulate the additional measurement procedure for the vector-row $\vec{x}^{\max}$ with the maximum error of prediction of the interval model, obtaining measurements with a minimum interval error according to the expression:

$$\max_{\vec{x}\in X}\left(\Delta\cdot\sqrt{\vec{\varphi}^T(\vec{x})\cdot(F_m^T\cdot F_m)^{-1}\cdot\vec{\varphi}(\vec{x})\cdot m}\right)\xrightarrow{F_m}\min . \qquad (19)$$

However, in contrast to the I_G-optimal sequential design procedure of an experiment, we choose a given point on a discrete set of vector-rows $\vec{x}_i$ (i = 1, ...,N) of matrix X. Denote the lower and upper bound for the resulting interval by $[\hat{y}^-_{\min};\hat{y}^+_{\min}]$.

We will carry out the above procedure for each interval equation of the "saturated" block. We get *p* new "saturated" blocks (*p*=*m*). As a result, for each of the *m* "saturated" blocks we obtain *m* values of maximum errors for the corresponding interval models:

$$\Delta_{\max}(F_m(p))=\max_{x_i, i=1,\dots,N}\left\{2\cdot\sum_{j=1}^{m}\left|\alpha_{jp}(\vec{x}_i)\cdot\Delta_j\right|\right\}, \quad , \qquad (20)$$
$$\vec{\alpha}_p^T(\vec{x}_i)=\vec{\varphi}^T(x_i)\cdot F_m^{-1}(p),\ p=1,\dots,m$$

where *p* is index, which means a number of “saturated” block, $F_m(p)$ is matrix of basic functions values for *p*-th block, $\alpha_{jp}(\vec{x}_i)$ is *i*-th component of vector $\vec{\alpha}$ for *p*-th “saturated” block.

To choose the optimal "saturated" block in this step, instead of a complex computational procedure (17), it is sufficient to choose from the *m* "saturated" blocks the one that provides the lowest value of the sequence (23), that is:

$$F_m^{\ opt}=\arg\min_{p=1,\dots,m}\left\{\Delta_{\max}(F_m(p)),\ p=1,\dots,m\right\}, \qquad (21)$$

Applying procedure (18), we obtain $\vec{x}^{\max}$ - the point at which the maximum error of the prediction by the interval model, the estimation of the set of values of parameters which is calculated from the chosen "saturated" block in the above-described method. Further iterations are continued until such a "saturated" block is obtained, the replacement of interval equations which does not lead to a decrease in the maximum prediction error by interval models.

The algorithm of realization of proposed method described below [8]:

Step 1. Choose the “saturated” block of ISLAE (5).

Step 2. Determination of the vector-row $\vec{x}^{\max}$ of the matrix X for solving the task (18).

Step 3. The iteration of the phased replacement of each of the *m* interval equations of the "saturated" block on the ISLAE (5) to the interval equation with a vector of values of input variables $\vec{x}^{\max}$ (forming a set of "saturated" blocks) and calculating maximum prediction errors (15) for interval models.

Step 4. Choose the optimal “saturated” block based on expression (21).

Transitioning to step 2.

Note that when transitioning to step 2, for a received "saturated" block, the estimations of the set of parameters of the interval model and the maximum error of the interval model constructed for this block will be known.

We implement a sequence of steps until the "saturated" block is received at the last step, any replacement of interval equations does not lead to a decrease in the maximum prediction error for the interval-based models constructed on its basis.

IV. Example of Application the Proposed Method for RLN Identification

The example of constructing a model of distribution on the surface of a surgical wound the maximum signal amplitudes as reaction to stimulation of surgical wound tissues described in article [5]. The structure of this mathematical model, obtained from the work [5], has the following form:

$$y(\vec{x}) = b_0 + b_1 \cdot \sin^2(x_1 \cdot x_2 \cdot \frac{\pi}{36}) + b_2 \cdot x_2 + b_3 \cdot (x_2^2) \quad (24)$$

A fragment of data obtained during the surgical operation on thyroid gland is given in Table 1 in [5].

We apply the method of selection the “saturated” block from ISLAE to find the most informative points.

As a result, the coordinates of the points of the saturated plan are found: [1.5;3], [3;6], [6;0.5], [6;6] (Fig. 2).

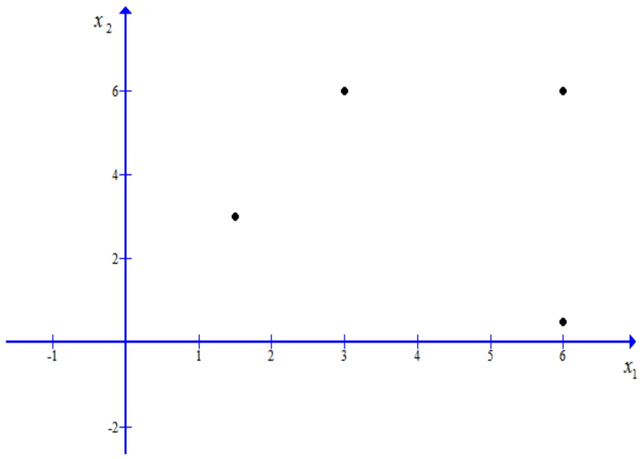


Fig. 2. The coordinates of the points found in the saturated plan for the RLN identification task

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VI. Conclusions

The method of design the saturated experiment with interval data on the principles of formation of a saturated block of the interval system of linear algebraic equations, as well as its application for the problem of locating RLN in the process of operation on the neck organs considered in this article. This saturated experimental plan allows to reduce the duration of surgical surgery by reducing the number of imitation points of a wound surgical wound to detect a RLN. If for the cases considered in other works construct a grid of m^2 stimulation points, then in the case of a saturated plan, the number of points is equal to the number of unknown coefficients of the model, which is tens of times smaller.

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