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The Approach to Processing of Biomedical Experimental Results

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Introduction

As a rule, experimental data distorted by disturbances can be described by unknown function $y = f(x)$. Graphs permit visual evaluation of qualitative properties of such process, despite disturbances and measurement errors. Graphs which depict the same process inside biological object can substantially differ one from the other due to specifics of object, implemented number of observations, noise level, etc. Without considering this, the shape of a curve characterizes parameters of the researched object or process.

When conducting biomedical research using "System 3 Multi-joint System" the analog signal is obtained which is imaged on the display screen. From the curve depicted on the screen it is possible to make decisions about muscle contraction and relaxation process It is possible to determine a series of parameters which are important to scientists, e.g. the magnitude of muscle force developed *Pt*, muscle contraction duration *CT*, its relaxation duration *RT* and series of other parameters.

At the output of the measurement device it is possible to obtain the value of analog signal of 2 kHz or less frequency [1]. The duration of measured signal can vary from fractions of a second to several seconds. Therefore some certain data sample is possible.

When performing investigations, force and time parameters are usually determined directly from curves seen on the monitor screen. Maximal force is determined according to peak of the curve, while CT and RT are determined according to curve maximum at 0.5 level. This takes a lot of time and measurement errors are possible due to operator actions, eye position in respect of the screen and other factors.

In order to determine signal parameters, it could be reasonable to apply algorithmic rules to the measurement process. For this reason it is required to approximate the signal using some certain empiric function at first.

Several methods can be used to approximate experimental data. Particular method is selected after evaluating the nature of experimental data. In considered case, this is the variation of the output parameter over time $y = (t)$, and it could be a function with one or several extremes.

Bezier curves can be applied in order to describe experimental curves [2], by using neural networks to recognize contours. The curve is described using polynomial, the coefficients of which, when curves are flat, can be calculated using rapid calculation technique which was offered earlier [2].

Good approximation results are also obtained when using hierarchical nonlinear approximation scheme [3]. When this method is applied directly, required computer resources increase; otherwise an appropriate emulator with the set of input functions suitable for particular case needs to be created. In any case, as it is indicated in [3], adjacent maximums are approximated as a single extreme. More precise approximation is possible in some certain part of a function [4]. In study [5] was proposed polynomial curve fitting with varying real powers method, but, the number of adapted parameters is bigger that parameters of traditional polinomials.

Methods and samples

The unknown function can be written as

$$y = (x, a, b, c, ...), \tag{1}$$

where x – independent variable; a, b, c – function parameters.

In case of biomedical measurements, the parameters of curves obtained according to measurement data vary considerably. Therefore empiric function has to be selected for each measurement. Furthermore, it has to be done real-time. For this reason it is purposeful to select functions and calculate their parameters using methods which do not require a lot of resources.

We will consider that the deviations of experimental data in respect of the scatter plot of empiric function $y = f(x)$, which may emerge due to measurement errors, correspond to normal distribution. Then the function value

y_i, which corresponds to value x_i, can be considered as a value of a random quantity Y_i with normal distribution

$$N(f(x_i);\sigma)\,, \qquad (2)$$

where $f(x_i)$ – the value of empiric function at the point x_i; σ_i – the standard deviation, determined by the measurement error.

It is possible to assume that the measurement precision is equal at all points ($\sigma_i = \sigma, i = 1,2,3,...n$).

The condition of maximum similarity of empiric function and experimental data can be written as

$$\sum_{i=1}^{n}(y_i - f(x_i))^2 = \min. \qquad (3)$$

By using the condition (2), it is possible to search for parameters a, b, c of empiric function $y=f(x, a, b, c, \ldots)$.

Then we can write condition

$$\sum_{i=1}^{n}(y_i - f(x_i,a,b,c,...))^2 = \min. \qquad (4)$$

Function (3) will reach minimum, when the function S=S(a, b, c, . . .) also reaches minimum, i.e. when

$$\frac{\delta S}{\delta a}=0,\quad \frac{\delta S}{\delta b}=0,\quad \frac{\delta S}{\delta c}=0, \qquad (5)$$

With the help of condition (4) we can form the system of equations:

$$\begin{cases} \sum_{i=1}^{n}(y_i - f(x_i,a,b,c,...))\cdot\left(\frac{\delta f}{\delta a}\right)_{x=x_i} = 0, \\ \sum_{i=1}^{n}(y_i - f(x_i,a,b,c,...))\cdot\left(\frac{\delta f}{\delta b}\right)_{x=x_i} = 0, \\ \sum_{i=1}^{n}(y_i - f(x_i,a,b,c,...))\cdot\left(\frac{\delta f}{\delta c}\right)_{x=x_i} = 0, \\ \ldots\ldots\ldots\ldots\ldots\ldots, \end{cases} \qquad (6)$$

after solving which it is possible to calculate the function parameters a, b, c, . . . For this purpose it is required to have exact expression of the function $y = (x,a,b,c,...)$ [5].

Assume that the searched function is a polynomial of n-th order

$$y(x) = k_n + k_{n-1}x + k_{n-2}x^2 + \ldots + k_1 x^{n-1} + k_0 x^n. \qquad (7)$$

Typical image of the function seen on the screen of the measurement device, when muscles are stimulated using single pulse, is shown in Fig. 1.

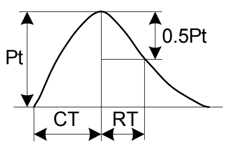

Fig. 1. Typical curve on monitor screen [6] (*Pt*, *CT*, *RT* – measured parameters)

Measured signal is obtained from Biodex multi-joint system 3. The Analog Signal Access port is an output of analog signals of velocity, torque and position data in real-time directly from the motor control Digital Signal Processor (DSP). A synchronization pulse is issued whenever the real-time data is updated.

Parameters *Pt*, *CT* and *RT* are measured visually, by placing respective vertical and horizontal markers. Consequently the measurement lasts for quite a long time; additionally, grid step values and operator experience influence the measurement results.

After completing input signal digitization, the measurement data processing using digital methods becomes possible. A signal of type amplitude-time $y=f(t)$ is obtained.

Thus after selecting polynomial for the approximation of function $y=f(t)$ and after calculating polynomial coefficients k_i, it is possible to find value of a function maximum – *Pt* and 0.5*Pt*, and also to calculate time intervals *CT* and *RT*.

If the muscle is stimulated using pulse series, then a more complex reaction signal is received, as it is shown in Fig. 2.

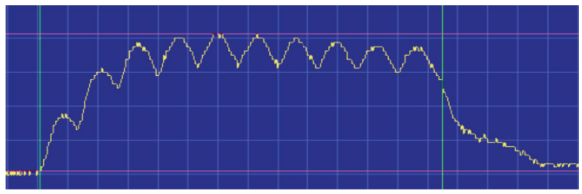

Fig. 2. A signal as a result of a reaction to a complex stimulus [6]

By repeating the stimulus signal, slightly changed signal is obtained. Such signals for the purposes of analysis can be attributed to random signals.

In this case it is more relevant to approximate the experimental function $y=f(t)$ using not polynomial, but by applying the signal envelope detection methods [7].

In the range of period the signal model can be described as

$$b(t) = E(t_i)\cdot n(t_i)\,, \qquad (8)$$

where $E(t_i)$ – the slowly changing envelope; $n(t_i)$ – Gaussian process with defined frequency range, zero mean and unitary dispersion, generated using moving sum method. Dispersion reconstruction error does not exceed ε = 0.05 [7].

The standard deviation variation function of the wideband process can be considered as an envelope (8) of this process [7]. In this way the envelope detection procedure can be the following:

1. According to the statistical formula of standard deviation, the estimate is calculated directly

$$\sigma_b(t_i) = E(t_i)\,. \qquad (9)$$

2. Process *b* is transformed into process *d* and the estimate $P_d(t_i)$ of parameter *d* is determined, which is unambiguously related to $\sigma_b(t_i)$. If process *b* corresponds to Gaussian distribution, then *d* will match semi-Gaussian distribution [8].

Segment averaging/Linear filtering method would be the most suitable to detect signal envelope, considering its precision and performance [7]. In this work we will limit ourselves to analysis of approximation possibilities of signal generated as a reaction to one-time stimulus.

Experimental results were obtained by measuring the amplitude values on the monitor screen at 56 points of the curve. Amplitude (contraction torque) is measured in Nm, and time parameter in ms – amplitude values were sampled each 5 ms. Measurements were conducted by two operators and means of measurement results were taken for further processing.

Measurement results were: $Pt = 42 \pm 1$ Nm, $CT = 96 \pm 2$ ms, $RT = 76 \pm 2$ ms.

Sixth order polynomial was selected to approximate experimental results using gradual approach method, by decreasing the sum of deviation squares,

$$y = 5E\text{-}08x^6 - 1E\text{-}05x^5 + 0.0008x^4 - 0.028x^3 + 0.3212x^2 + 1.8465x + 0.4865, \qquad (8)$$

the coefficient values of which, used in calculations, are given in Table 1.

Table 1. Polynomial coefficient values

Coefficient	Value
k_0	0.4865093545149650
k_1	1.8465363161267300
k_2	0.321167784932413
k_3	2.79859239518956E-2
k_4	8.06231086762E-4
k_5	1.0276727712E-5
k_6	4.97575035E-8

Experimental results and function used in approximation is given in Fig. 3 for illustrative purposes.

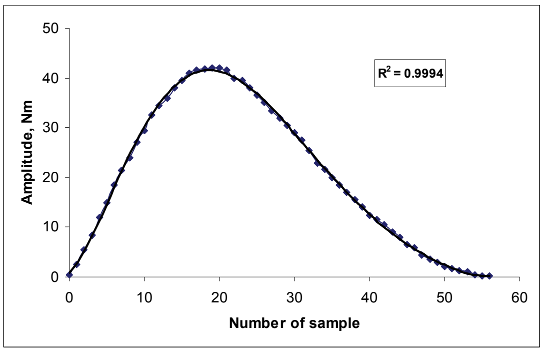

Fig. 3. Experimental results

Distribution of deviations between experimental results and approximating curve $\Delta y_i = (y_a - y_i)$ (residual plot) is shown in Fig. 4, and the sum of deviation squares was $\Sigma(y_a - y_i)^2 = 6.45$, here y_a – the calculated value of function (7) at point x_i.

When approximating experimental results using lower order polynomials, the sum of deviations increases significantly. Distribution of deviations after approximation using third order polynomial is presented in Fig. 5, and the sum of squared deviations was $\Sigma(y_a - y_i)^2 = 141.15$.

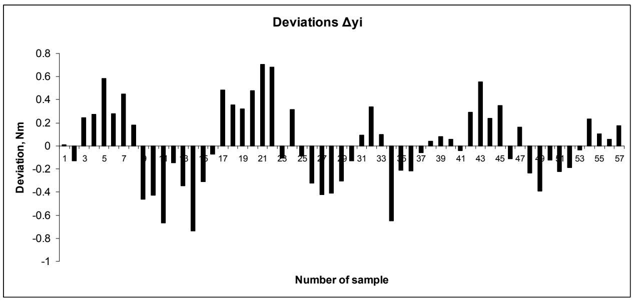

Fig. 4. Residual plot of deviations

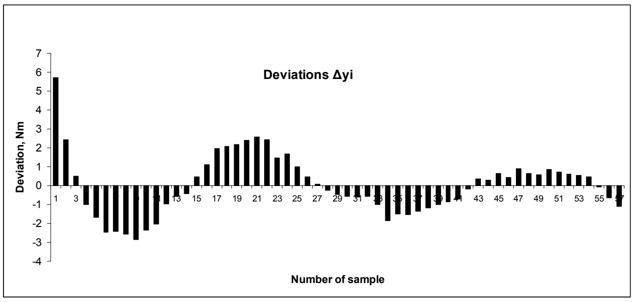

Fig. 5. Residual plot of squared deviations after approximation using third order polynomial

Distribution of relative errors expressed as percentage is given in Fig. 6, using sixth order polynomial.

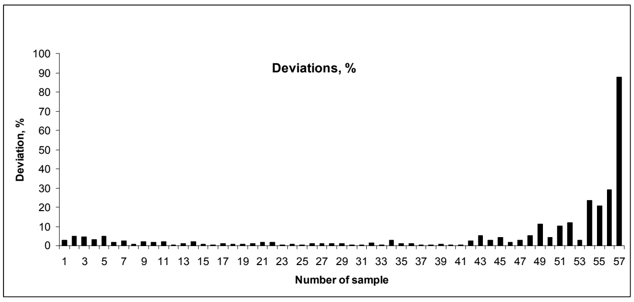

Fig. 6. Distribution of relative errors

Errors significantly increase after 48th sample. Deviation in % is increasing because is decreasing the measurement values and their sizes converge. Although this to the calculation precision of parameters *Pt*, *CT* and *RT* are influenced less, since in the given case data from 10th to 40th sample is used to calculate them. Deviation in % is increasing because is decreasing the measurement values and their sizes converge.

The sequence of steps in the calculation of parameters *Pt, CT* and *RT* is shown in Fig. 7.

The calculated values of parameters were: $Pt = 41.7$ Nm, $CT = 94.3$ ms, $RT = 78.4$ ms.

The maximum signal amplitude of +5V in measurement device Biodex multi-joint system 3 corresponds to analog-to-digital converter output code 512. Maximum signal is obtained under load of 680 Nm, and the sampling rate is 200 kHz [1].

Therefore 1st quantization level, or maximum resolution, corresponds to 1.328125 Nm, and sampling period is 0,05 ms; for this reason, when performing calculations using more data received from the system, it is possible to increase the evaluation precision of parameters *Pt, CT* and *RT*.

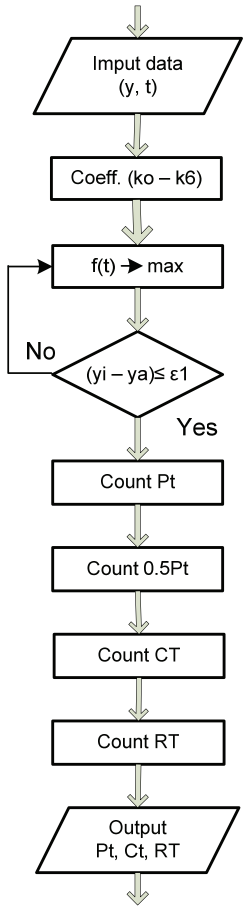

Fig. 7. Algorithm (sequence of steps) used to calculate parameters

Conclusions

It is advisable to use sixth order polynomial to approximate the function of reaction to one-time stimulus.

In order to evaluate parameters of signal generated as a reaction to multiple stimuli it s more purposeful to use signal envelope detection methods. It is likely, that Segment averaging/Linear filtering method would be the most suitable for this aim, considering precision and performance criteria.

When parameters *Pt*, *CT* and *RT* are determined using digital signal processing, the experiment duration decreases and also it is possible to eliminate the influence of operator actions on measurement results.

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The aim is to analyze possibilities to approximate the signal of muscle reaction to stimuli using analytical functions, and to calculate required parameters *Pt*, *CT* and *RT*. It was shown, that under impact of one-time stimulus pulse it is purposeful to use sixth order polynomial for approximation. Polynomial coefficients with no less than 16 decimal places should be used for calculations. Algorithm for calculation of parameters *Pt*, *CT* and *RT* was presented. It was shown, that in case of muscle stimulation using complex signal it is more advisable to use reaction signal envelope detection methods. Experimental and calculation results are presented. Ill. 7, bibl. 8 (in English; abstracts in English and Lithuanian).

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Darbo tikslas – išanalizuoti galimybes aproksimuoti raumenų reakcijos į stimuliavimą signalus analitinėmis funkcijomis ir jų pagrindu apskaičiuoti dominančius parametrus *Pt*, *CT* ir *RT*. Parodyta, kad veikiant vienkartiniam stimuliavimo impulsui, aproksimavimui tikslinga naudoti šeštos eilės polinomą. Skaičiavimams naudoti polinomo koeficientus su mažiau kaip 16 ženklų po kablelio. Pateiktas parametrų *Pt*, *CT* ir *RT* apskaičiavimo algorimas. Parodyta, kad stimuliuojant raumenį sudėtingu signalu, tikslingiau ieškoti reakcijos signalo gaubtinės. Pateikti eksperimentų ir skaičiavimų rezultatai. Il. 7, bibl. 8 (anglų kalba; santraukos anglų ir lietuvių k.).