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Construction Of Higher-Order Spline Functions, Digital Processing And Modeling Of Signals, And Their Comparative Analysis

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Abstract: In this work, numerical processing of signals using high-order spline models in the direction of the approximation theory of mathematical modeling, which plays an important role in the development of science, is considered one of the important and urgent issues, therefore, third-order, fifth-order, seventh-order Ryabenky spline models selected. We can also say that high-order Ryabenky spline models are effective and reliable mathematical models in digital signal processing. As an example, the functions obtained as an experiment and the initial values of the gastroenterological signal were obtained. Approximation of gastroenterological signals and functions, numerical processing of signals by obtained values, and results of comparative analysis are presented. From the results of the comparative analysis, it was analyzed that the results obtained in this study in digital processing of signals are better approximated by the seventh-order Ryabenky spline model among the results of digital processing of signals based on third-order, fifth-order, and seventh-order Ryabenky spline functions. The higher-order Ryabenky spline functions discussed in this paper can also be used in digital processing and processing of various medical and other signals.

Keywords— digital signal processing, spline models, medical signals, mathematic models, gastroenterological signals.

I.INTRODUCTION

Today, in the field of medicine, many studies are being conducted on monitoring human health and accurate and early diagnosis of diseases in patients. Ongoing research shows that medical signal processing, digital processing of signals can provide high-quality and effective diagnosis. It is emphasized that this is important and one of the most urgent issues of our time. Since the issue here is about human health, it encourages scientists to conduct non-stop research in medicine, modeling, modern technology and other fields. Among them, the researchers conducted in digital processing of signals are also considered important. The ongoing research is inextricably linked with many directions. For example: mathematical modeling, digital signal processing, medicine and several other fields. Analyzing such factors, the application of spline functions, which is considered an important and leading mathematical tool of approximation theory, ranks high in terms of relevance and today brings good results in several fields of science and technology. Many scientists have cited this in their research [8,10,13,15,16,18]. Therefore, the application of spline functions in solving the problems considered in this article is intended. In the next step, we will consider the

construction and implementation of spline functions.

II. CONSTRUCTION OF HIGHER ORDER SPLINE FUNCTIONS

If the function under consideration is sufficiently smooth, then it is desirable to approximate it with splines of a higher degree so that the convergence is faster. For this purpose, the error of approximating the function by splines of the seventh degree of Ryaben'kiy has been investigated. Continuing the study, the splines of the seventh degree of Ryabensky were obtained [1,4,5,6].

In this paper, using quadrature formulas, we will calculate estimates of their error.

Let p>0 be a fixed integer, $f(x) \in C^q(-\infty,\infty)$ and $f(x)=f(ih),(i=0,\pm1,\pm2,\dots)$ the trace of a function on a uniform one-dimensional grid [4,5,9].

Ryaben'kii's papers describe the operator L that maps $f(ih)$ to the function Sph(x). defined everywhere and being an interpolation spline of degree 2p+1 of defect p+1. To estimate the error in the one-dimensional case with respect to the error $f(x)$ - Sph(x) and order derivatives, the following estimate follows:

$$\left|f^{(r)}(x)-S_{ph}^{(r)}(x)\right| \le h^{q-r}K(p)\,sup_x\left|f^{(q)}(x)\right|. \quad (1)$$

where the constant $k(p)$ depends only on p.

For any spline Sph(x) can be written explicitly in terms of the values of the function $f(ih)$, so it is convenient for applications. In contrast to Hermitian splines, these splines can also be used to approximate C[a,b] functions [2].

In the works of Sodolev and Ryaben'kiy, for $x_i, \le x \le x_{i+1}$ the following expression is given for the function Sph(x) [3,6]

$$S_{ph}(x)=\sum_{j=0}^{p}\sum_{k=0}^{p-j}\frac{(p+k)!}{k!j!p!}\left[a_{pj}(x_i)t^{j+k}(1-t)^{p+1}+(-1)^j a_{pj}(x_{i+1})t^{p+1}(1-t)^{j+k}\right]. \quad (2)$$

Where: $t=\frac{x-x_i}{h}, a_{p0}(x_i)=f(x_i)$

$$a_{pj}=j!\sum_{k=j}^{p}\frac{\Delta f(x_i)}{k!}S(k,j)j \ge 1 \quad (3)$$

$S(k,j)$ Stirling numbers of the first kind.

Relationship between Newtonian and ordinary powers formulas

$$y^0=y^{[0]}; y^n=\sum_{k=1}^{n}S(n,k)y^{[k]}, n=1,2,\dots$$

$$y^{[0]}=y^{[n]}; y^n=\sum_{k=1}^{n}S(n,k)y^k, n=1,2,\dots$$

where $S(n,k)$ and $S(k,j)$ are the so-called Sterling numbers of the first and second kind, respectively

Precisely the following identity

$$y^k=\sum_{i=1}^{k}\frac{y^{[k]}}{i!}\Delta^i O^k \quad (4)$$

where: $y^{[k]}=y(y-1)(y-2)\dots(y-k+1)$, $\Delta^i O^\alpha=\sum_{k=1}^{i}(-1)^{i-e}e_j^{\,e}\,e^k$

$y_{(n=3)}{}^{[n]}=\sum_{k=1}^{n=3}S(n,k)\,y^k$;

$y[k]=y(y-1)(y-2)\dots(y-k+1)$

n=1; $y^{[1]}=\sum_{k=1}^{1}S(1,1)\,y'=S(1,1)y'=y$

n=2; $y^{[2]}=\sum_{k=1}^{2}S(2,k)\,y^k=S(2,1)y+S(2,2)y^2=y(y-1)$

n=3; $y^{[3]}=\sum_{k=1}^{3}S(3,k)\,y^k=S(3,1)y+S(3,2)y^2+S(3,3)y^3=y(y-1)(y-2)$

general view of Newtonian and ordinary powers [9,11,15,17]

$$y^{[k]} = S(k,1)y + S(k,2)y^2 + S(k,3)y^3 + \ldots\ldots + S(k,k-1)y^{k-1} + S(k,k)y^k$$

$$y^{[k]} = y(y-1)(y-2)(y-3)\ldots(y-k+1)$$

$$y^{[k+1]} = y(y-1)(y-2)(y-3)\ldots(y-k+1)(y-k)$$

$$y^{[k+1]} = S(k+1,1)y + S(k+1,2)y^2 + S(k+1,3)y^3 + \ldots\ldots + S(k+1,k)y^k + S(k+1,k+1)y^{k+1}$$

$$y^{[n]} = [\sum_{n=1}^{k} S(k,n)\, y^n = (S(k,1)y + S(k,2)y^2 \ldots\ldots + S(k,k-1)y^{k-1} + S(k,k)y^k)(y-k)(S(k,1)y + S(k,2)y^2 \ldots\ldots + S(k,k-1)y^{k-1} + S(k,k)y^k)(y-k)$$

$$S(0,0) = 0 \ldots S(k,0) = 0 \ldots S(k,k) = 1 \ldots, k \geq 1 S(k+1,j)$$

$$S(k+1,j) = S(k,j-1) - kS(k,j), j = 1,k = S(k,j-1) - kS(k,j), j = 1,k$$

Recursive formula for calculating Stirling 1-kind:

$$\begin{cases} y^{[n]} - \text{newton wall} \\ y^n - \text{ordinary wall} \\ \left(\text{connection between them inset connection between numbers Stilngga of the 1st and 2nd kind}\right) \end{cases}$$

$y^{[k]}$, $y^{[k]} = y(y-1)(y-2)(y-3)\ldots(y-(k-1))$

$$y^{[0]} = y^0 = 1$$

$$y[1] = y$$

$$y^{[2]} = y(y-1) = y^2 - y$$

$$y^{[3]} = y(y-1)(y-2) = (y^2-y)(y-2) = y^3 - y^2 - 2y^2 + 2y = y^3 - 3y^2 + 2y =$$

$$\sum_{k=1}^{3} S(n,k)\, y^k = S(3,3)y^3 + S(3,2)y^2 + S(3,1)$$

$$S(3,3) = 1, \ \rightleftarrows\rightleftarrows \ S(3,2) = -3, \ \ S(3,1) = 2$$

$y^{[n]} = \sum_{k=1}^{n} S(n,k)\, y^k$ here the $S(n,k)$ is the Stirling number of the 1st kind

$y^n = \sum_{k=1}^{n} S(n,k)\, y^{[k]} = \sum_{k=1}^{n} \frac{\Delta^k O^n}{k!} y^{[k]}$ – here the $S(n,k)$ is the Stirling number of the 1st kind

$y^{[n]} = \sum_{k=1}^{n} S(n,k)y^k = S(n,1)y + S(n,2)y^2 + S(n,3)y^3 + \ldots\ldots + S(n,n)y^n$ here the $S(n,k)$ is the Stirling number of the 1st kind.

Example n=1

1. $y^{[1]} = \sum_{k=1}^{1} S(n,k)\, y^k = S(1,1)y'$

2. $y^{[1]}$ = y when comparing received $S(1,1)y^1 = y^1 \Rightarrow S(1,1) = 1$

n=2

$$y^{[2]} = y(y-1) = y^2 - y \quad (1)$$

$$y^{[2]} = \sum_{k=1}^{2} S(2,k)y^k = S(2,1)y + S(2,2)y^2 \quad (2)$$

$(1) = (2)$

$1y^2 - y = S(2,2)y^2 + s(2,1)y \Rightarrow S(2,2) = 1 \ \ S(2,1) = -1$

n=3

$$y^{[3]} = \sum_{k=1}^{3} S(3,k)y^k = y(y-1)(y-2) = y^3 - 3y^2 + 2y \Rightarrow$$

$$\Rightarrow S(3,1) = 2; \ S(3,2) = -3; \ S(3,3) = 1$$

$$S(3,1)y + S(3,2)y^2 + S(3,3)y^3 \Rightarrow S(k,0) = 1; S(k,k) = 1$$

$$S(k+1,j) = S(k,j-1) - kS(k,j), \ \ (j = \overline{1,k})$$

The spline of the third degree of Ryabenky [2,4,5,9], on the segment $[x_i; x_{i+1}]$

$S_3(x) = \phi_1(t)f(x_i) + \phi_2(t)f(x_{i+1}) + \phi_3(t)f(x_{i+2})$. (5)

here: $\phi_1(t) = (1-t)^2(1+t)$,

$$\phi_2(t) = t(1+2t-2t^2),$$

$$\phi_3(t) = -t^2(1-t)$$

p=1

$$S_{1h}(x) = \sum_{j=0}^{1}\sum_{k=0}^{1-j}\frac{(1+k)!}{k!\,j!\,1!}\big(a_{1j}(x_i)t^{j+k}(1-t)^{1+1} + (-1)^j a_{1j}(x_{i+1})t^{1+1}(1-t)^{j+k}\big) =$$

$$= \sum_{k=0}^{1}\frac{(1+k)!}{k!\,1!\,1!}(a_{10}(x_i)t^{0+k}(1-t)^2 + (-1)^0 a_{10}(x_{i+1})t^2(1-t)^k) +$$

$$+ \sum_{k=01}^{1-0}\frac{1!}{1!\,0!\,1!}(a_{11}(x_i)t^{1+0}(1-t)^2 + (-1)^1 a_{11}(x_{i+1})t^2(1-t)^{1+0}) =$$

$$= \frac{1!}{0!\,1!\,1!}(a_{10}(x_i)t^0(1-t)^2 + (-1)^0 a_{10}(x_{i+1})t^2(1-t)^0) +$$

$$+\frac{2!}{1!\,1!\,1!}\big(a_{10}(x_i)t(1-t)^2 + (-1)^0 a_{10}(x_{i+1})t^2(1-t)\big) +$$

$$+a_{11}(x_i)t(1-t)^2 - a_{11}(x_{i+1})t^2(1-t) =$$

$$= a_{10}(x_i)(1-t)^2 + a_{10}(x_{i+1})t^2 + 2a_{10}(x_i)t(1-t)^2 + 2a_{10}(x_{i+1})t^2(1-t) +$$

$$+a_{11}(x_i)t(1-t)^2 - a_{11}(x_{i+1})t^2(1-t) =$$

$$= a_{10}(x_i)(1-t)^2(1+2t) + a_{10}(x_{i+1})t^2(3-2t) + a_{11}(x_i)t(1-t)^2 - a_{11}(x_{i+1})t^2(1-t)$$

$$t = S_{1h}(x) = a_{10}(x_i)(1-t)^2(1+2t) + a_{10}(x_{i+1})t^2(3-2t) +$$

$$= a_{11}(x_i)t(1-t)^2 - a_{11}(x_{i+1})t^2(1-t)$$

$$a_{10}(x_i) = f(x_i), \Delta f(x_i) = f(x_{i+1}) - f(x_i)$$

$$a_{11}(x_i) = 1!\sum_{k=1}^{1}\frac{\Delta f(x_i)}{1!}S(1,1) = f(x_{i+1}) - f(x_i), S(1,1) = 1$$

$$a_{11}(x_{i+1}) = f(x_{i+2}) - f(x_{i+1})$$

$$S_{1h}(x) - S_3(x) = f(x_i)(1-t)^2(1+2t) + f(x_{i+1})t^2(3-2t) + +\big(f(x_{i+1}) - f(x_i)\big) + (1-t)^2 - \big(f(x_{i+2}) - f(x_{i+1})\big)t^2(1-t) =$$

$$= ((1-t)^2(1+2t)t(1-t)^2)f(x_i) + \big(t^2(3-2t) + t(1-t)^2 + t^2(1-t)\big)f(x_{i+1}) - -t^2(1-t)f(x_{i+2}) = \phi_1(t)f(x_i) + \phi_2(t)f(x_{i+1}) + \phi_3(t)f(x_{i+2})$$

$$\phi_1(t) = (1-t)^2(1+t),\ \ \phi_2(t) = t(1+2t-2t^2),\ \ \phi_3(t) = -t^2(1-t)$$

III. COMPARATIVE ANALYSIS OF DIGITAL SIGNAL PROCESSING USING HIGHER ORDER SPLINE FUNCTIONS.

Above, we considered the construction of the third-order Ryabenikov spline function [4,5,9,21], and thus the 5th and 7th-order models of this spline function were also constructed. The constructed models are shown in Figure 1 in the Maple program. Now we will consider the application and comparative analysis of 3rd, 5th and 7th order Ryabenikov spline functions to gastroenterological signals [17,19,20,22,23].

$$SR_3(x) = h\sum_{i=1}^{N} f(ih) + \frac{5}{12}h\big(f(0) - f(1)\big) + \frac{1}{12}h\big(f(h) - f(1+h)\big) \quad (6)$$

here: $f(x), x = ih, i = 1\ldots N$

$$SR_5(x) = h\sum_{i=1}^{N} f(ih) + \frac{43}{120}h\big(f(0) - f(1)\big) + \frac{1}{5}h\big(f(h) - f(1+h)\big) - \frac{7}{120}h\big(f(2h) - f(1+2h)\big) \quad (7)$$

here: $f(x), x = ih, i = 1\ldots N$

$$SR_7(x) = h\sum_{i=1}^{N} f(ih) + \frac{549}{1680}h\big(f(0) - f(1)\big) + \frac{523}{1680}h\big(f(h) - f(1+h)\big) -$$

$$\frac{313}{1680}h\big(f(2h)-f(1+2h)\big)+\frac{81}{1680}h\big(f(3h)-f(3+h)\big) \quad (8)$$

here: $f(x), x=ih, i=1\ldots N$

Table 1 presents the comparative analysis results of the $f(x)=x^7$ function selected as an experiment on the basis of the spline functions of the 3rd, 5th, and 7th orders given above with integral values at different values of N.

N	f(x)	SR3(x)	SR5(x)	SR7(x)	f(x)-SR3(x)	f(x)-SR5(x)	f(x)-SR7(x)
10	0,125	0,12289827	0,12310161	0,1239654	2,10E-03	1,90E-03	1,03E-03
20	0,125	0,12476026	0,124847401	0,124955721	2,40E-04	1,53E-04	4,43E-05
30	0,125	0,1249311	0,124961806	0,12499238	6,89E-05	3,82E-05	7,62E-06
40	0,125	0,12497137	0,124985271	0,124997755	2,86E-05	1,47E-05	2,24E-06
50	0,125	0,12498548	0,124992869	0,12499912	1,45E-05	7,13E-06	8,801E-07
60	0,125	0,12499165	0,124996028	0,124999588	8,35E-06	3,97E-06	4,121E-07
70	0,125	0,12499476	0,124997567	0,124999782	5,24E-06	2,43E-06	2,177E-07
80	0,125	0,1249965	0,124998404	0,124999874	3,50E-06	1,60E-06	1,256E-07
90	0,125	0,12499755	0,124998898	0,124999226	2,45E-06	1,10E-06	7,742E-07
100	0,125	0,12499822	0,124999207	0,124999497	1,78E-06	7,9302E-07	5,029E-07

As can be seen from the table above, the results obtained using higher-order spline functions are very close to the experimental results of the function. This closeness indicates a high accuracy and reliability of higher-order spline modeling techniques. Consequently, employing the selected spline model within medical diagnostics and research is expected to yield highly effective and reliable results. Accurate modeling ensures that healthcare professionals can make precise and informed decisions based on the analyzed data. In the next section, we will delve deeper into the practical application of this spline-based modeling technique, specifically addressing gastroenterological and cardiological signals. Additionally, a thorough comparative analysis will be presented to demonstrate the effectiveness of spline-based models in these specialized medical fields.

In cardiology, it is particularly crucial to accurately measure heartbeat amplitude, as it plays a significant role in monitoring human health and diagnosing heart-related diseases. Any inaccuracies in measuring cardiac signals could potentially lead to misdiagnosis or delayed treatments, thereby emphasizing the importance of precise computational modeling methods such as higher-order spline functions.

Similarly, gastroenterological signals hold significant importance in diagnosing diseases of internal organs and evaluating the effectiveness and progression of therapeutic interventions. Precise spline modeling techniques allow for detailed interpretation of these signals, enhancing the reliability of medical assessments and treatment

plans. By accurately analyzing and interpreting gastroenterological data, healthcare providers can significantly improve the outcomes of patient treatments, thus underscoring the practical benefits and clinical value of higher-order spline modeling methods.

Table 2 presents the values of gastroenterological signals and their comparative analysis restored on the basis of the higher-order spline function.

N	*f(x)*	*SR3(x)*	*SR5(x)*	*SR7(x)*	*f(x)-SR3(x)*	*f(x)-SR5(x)*	*f(x)-SR7(x)*
10	0,25	0,24975	0,2499	0,25	2,50E-04	1,00E-04	0
20	0,25	0,24996875	0,2499875	0,25	3,13E-05	1,25E-05	0
30	0,25	0,24999074	0,249996296	0,25	9,26E-06	3,70E-06	1E-15
40	0,25	0,24999609	0,249998438	0,25	3,91E-06	1,56E-06	1E-15
50	0,25	0,249998	0,2499992	0,25	2,00E-06	0,0000008	1E-15
60	0,25	0,24999884	0,249999537	0,25	1,16E-06	4,62963E-07	0
70	0,25	0,24999927	0,249999708	0,25	7,28863E-07	2,91545E-07	0
80	0,25	0,24999951	0,249999805	0,25	4,88281E-07	1,95313E-07	0
90	0,25	0,24999966	0,249999863	0,25	3,42936E-07	1,37174E-07	1E-15
100	0,25	0,24999975	0,2499999	0,25	0,00000025	0,0000001	0

From the results obtained from Table 2, it can be seen that from the higher-order spline functions, the seventh-order spline function returned the values for which the values of the function were the least different from the true values. So digital processing of signals through this model gives good results in the considered medical field. You can see this from the results in the table above.

CONCLUSION

In this article, we considered the construction of spline functions of the third, fifth, and seventh degrees. In addition, a comparative analysis was conducted with the function values obtained as an experiment. Based on the obtained results, the effectiveness of the considered model was evaluated, its application to gastroenterological signals and a comparative analysis was presented. From the obtained results, the maximum value of the differences of the results obtained by the spline function of the third degree from the actual values was equal to 2.5E-04, and in the spline function of the fifth degree, it was equal to 1.0E-04. Among the considered models, the spline with the highest efficiency and accuracy is the seventh-order spline function, and it is not difficult to see this from the obtained results. This is of great importance in digital processing of medical signals.

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