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CONSTRUCTION OF CORRELATION MODELS OF OSCILLATORY PROCESSES BY AN ALTERNATIVE METHOD

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Abstract
This article examines economic processes with correlational dependencies that change over time according to a harmonic law, and it also proposes a method for determining the period, phase, and frequency of the oscillations in these processes. The article proposes a method for determining the coefficients A and B in the harmonic function, which was obtained as a result of research.

Keywords: Differential equation, finite differences, period of oscillation, frequency of oscillation, harmonic functions, cyclicity of fluctuations in crop yields, oscillation phase.

Introduction

Many processes in nature occur on the basis of oscillatory laws. Based on the results of experiments, the main characteristics, such as the oscillation period, frequency, oscillation phase and amplitude, are easily determined if the dependence is functional. For example, oscillations of electromagnetic waves, oscillations of a mathematical pendulum. However, when studying processes with correlational dependencies, the task becomes more complex, as it requires determining the period of oscillation, amplitude, and other parameters. Additionally, it is necessary to analyze and compare large volumes of data over an extended period.

In this paper, an attempt is made to answer the following questions:

1. Is it possible to determine whether the process $y_i=f(x_i)$ is harmonic if the results of experiments on the process T at points x_i and y_i are known? Is there a mathematical criterion to verify the correctness of this statement?
2. How to determine the method for finding the period of oscillation, frequency, and phase of oscillation?
3. How can the coefficients A and B be determined if the harmonic function obtained from the study is $y = A\sin(\omega x) + B\cos(\omega x)$?

MATERIALS AND METHODS

When solving practical problems, researchers often face the question of whether a given process is an oscillatory process. This question arises in several cases, such as: studying the yield of agricultural crops, examining the fluctuation in demand for goods and services depending on the season, and studying the periodicity of earthquake occurrences in seismically active zones.

Oscillatory processes of agricultural crop yields have been examined in the scientific works of Russian researchers, in which the regularity of grain crop yield fluctuations has been established [1,2,3]. Based on the study of long-term time series, the authors identified the existence of a certain yield fluctuation cycle and established the regularity of this process. Additionally, several articles were published in the journal "Хлопководство" (Cotton Cultivation) where an attempt was made to prove the existence of cyclical fluctuations in crop yields across all cotton-growing republics of the former Soviet Union. It was also demonstrated that these regularities apply to other agricultural crops as well. To prove that a particular process under study is a cyclical process, it is necessary to analyze a large amount of statistical data, check their synchrony, compare the graphs of these phenomena, and much more.

RESULTS AND DISCUSSION

The question arises: is it possible to determine if the process under study is an oscillatory (harmonic) process if the observation results are known at limited points? For this, there is a finite number of points x_i and y_i, where $i = \overline{1, N}$. A mathematical criterion also needs to be developed, such that when it is satisfied, the function $y_i = f(x_i)$ will be exactly harmonic, and not some other function.

Let us assume that we have a function $y = f(x)$ and that this function is harmonic::

$$y = A\sin\frac{2\pi x}{T} + B\cos\frac{2\pi x}{T}$$

To determine the criterion, we calculate the derivatives $\frac{dy}{dx}$ and $\frac{d^2y}{dx^2}$:

$\frac{dy}{dx} = A\frac{2\pi}{T}\cos\frac{2\pi x}{T} - B\frac{2\pi}{T}sin\frac{2\pi x}{T}$ and $\frac{d^2y}{dx^2} = -A\left(\frac{2\pi}{T}\right)^2 sin\frac{2\pi x}{T} - B\left(\frac{2\pi}{T}\right)^2\cos\frac{2\pi x}{T}$.

Taking into account that $y=A\sin\frac{2\pi x}{T}+Bcos\frac{2\pi x}{T}$, we have

$\frac{d^2y}{dx^2} = -\left(\frac{2\pi}{T}\right)^2\left(Asin\frac{2\pi x}{T} + B\cos\frac{2\pi x}{T}\right)$ or $\frac{d^2y}{dt^2} = -\left(\frac{2\pi}{T}\right)^2 y$.

In other words, $\frac{d^2y}{dx^2} = y'' = -\omega^2 y$, where $\omega = \frac{2\pi}{T}$. Here, T is the period of oscillation, and $\frac{1}{T}$ is the frequency of the oscillatory process under consideration. From this, it follows that:

$$\frac{y''}{y} = -\omega^2 = const. \qquad (1)$$

Condition (1) is the criterion for the harmonicity of the process $y = f(x)$.

Thus, if for the process $y = f(x)$, the ratio $\frac{y''}{y}$ remains a constant, then this process is a harmonic process.

Since we do not have the specific function of the process $y_i = f(x_i)$, but only the observation results at certain points x_i and y_i, where $i = \overline{1, N}$, we will try to replace $\frac{dy}{dx}$ и $\frac{d^2y}{dx^2}$ with finite differences, which can be expressed in terms of x_i and y_i, where $i = \overline{1, N}$.

If $y = f(x)$ is a continuous function and has continuous first and second derivatives, then from the definition of the derivative $y' = f'(x_0)$

$$\lim_{\Delta x \to 0} \frac{y(x_0 + \Delta x) - y(x_0)}{\Delta x} = \lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x} = f'(x_0) = y'$$

we have:

$$\frac{y(x_0+\Delta x)-y(x_0)}{\Delta x} \approx f'^{(x_0)} = y' \text{ or } \frac{\Delta y}{\Delta x} \approx f'^{(x_0)} = y';$$

By the definition of the second derivative $y'' = f''(x_0)$

$$\lim_{\Delta x \to 0} \frac{y'(x_0 + \Delta x) - y'(x_0)}{\Delta x} = \lim_{\Delta x \to 0} \frac{\Delta^2 y}{\Delta x^2} = f''(x_0) = y''$$

we have:

$$\frac{\Delta^2 y}{\Delta x^2} \approx f''^{(x_0)} = y''.$$

Therefore, the derivatives can be approximately replaced by finite differences:

$$y' = \frac{dy}{dx} \approx \frac{\Delta y}{\Delta x}, \; y'' = \frac{d^2y}{dx^2} \approx \frac{\Delta^2 y}{\Delta x^2}.$$

Based on this, our criterion for the cyclicity of the function takes the following form: if the results of the experiment x_i and y_i, are known, then a necessary condition for the cyclicity of the process is the fulfillment of the condition:

$$\frac{\Delta^2 y}{\Delta x^2} / \text{y} = \text{const.}$$

The theory outlined above can be examined using the following specific example. In this case, the condition $\frac{\Delta^2 y}{\Delta x^2}$/y =const plays an important role in the correct selection of the function $y = f(x)$.

Table №1.

The coincidence of the values of the harmonic function y_1 and the straight line y_2 within specific intervals of the values of «x»

x	y_1 = 3sin(2*3,14*x/5)	y_2 = 2,8591x + 0,2151	y_1- y_2
0,035	0,131837528	0,3151685	0,183331
0,07	0,263420324	0,415237	0,151817
0,105	0,394494146	0,5153055	0,120811
0,14	0,524805739	0,615374	0,090568
0,175	0,654103318	0,7154425	0,061339
0,21	0,782137057	0,815511	0,033374

0,245	0,908659575	0,9155795	0,00692
0,28	1,033426407	1,015648	-0,01778
0,315	1,156196483	1,1157165	-0,04048
0,35	1,276732591	1,215785	-0,06095
0,385	1,394801834	1,3158535	-0,07895
0,42	1,510176082	1,415922	-0,09425
0,455	1,622632412	1,5159905	-0,10664
0,49	1,73195354	1,616059	-0,11589
0,525	1,837928239	1,7161275	-0,1218
0,56	1,940351747	1,816196	-0,12416
0,595	2,039026165	1,9162645	-0,12276
0,63	2,133760837	2,016333	-0,11743
0,665	2,224372719	2,1164015	-0,10797
0,7	2,310686734	2,21647	-0,09422
0,735	2,392536109	2,3165385	-0,076
0,77	2,469762696	2,416607	-0,05316
0,805	2,542217281	2,5166755	-0,02554
0,84	2,609759868	2,616744	0,006984
0,875	2,672259955	2,7168125	0,044553
0,91	2,729596781	2,816881	0,087284
0,945	2,78165956	2,9169495	0,13529
0,98	2,828347698	3,017018	0,18867
1,015	2,869570988	3,1170865	0,247516

Table №1 presents the experimental data connecting x_i and y_i. At first glance, it appears to be a typical linear relationship $y=a_0+bx$ between x and y. The data was processed using traditional methods, and the following result was obtained: y_2 =2,8591x+1,2151. The correlation coefficient is r=0,98, and the difference between the actual and calculated values $|y_a - y_c| \approx 0$. But in reality, this is not the case. The given data represents the values of the function y_1=3sin(1,256x). If we examine the values of the function y_2=2,8591x+0,2151 and the values of y_1=3sin(1,256x) on the graph (Fig. 1), we can see that they are virtually identical.

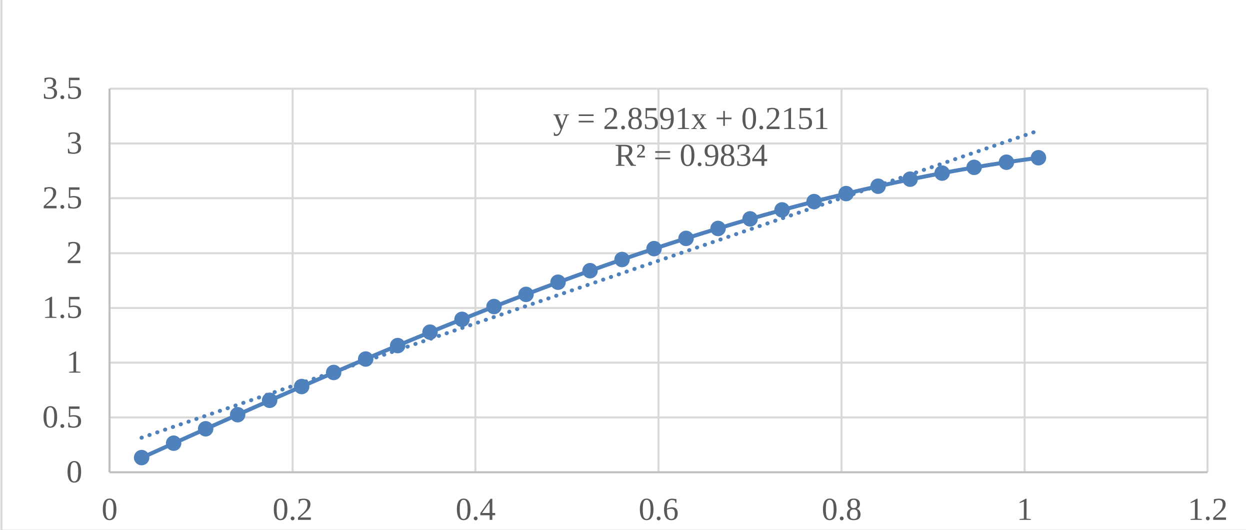

Figure 1. Comparison of real and modeled values.

This is the main reason for our research. In other words, it is necessary to find a mathematical statement that provides a clear answer to the question about the form of the relationship between the data x_i and y_i : linear $y=a_0+bx$ or harmonic $y=A\sin\frac{2\pi x}{T}+B\cos\frac{2\pi x}{T}$. The necessary condition for the existence of a harmonic dependence between x_i and y_i was stated in formula (1). To verify the correctness of our theory, let's consider an example presented in Table №2. In the seventh column of this table, the values of the second-order finite difference $\frac{\Delta^2 y_i}{\Delta x^2}/y$ are calculated, and their average value is computed as $-1{,}13= -\omega^2$, from which $\omega = \sqrt{1{,}13} = 1{,}06$. Since $\omega^2 = \left(\frac{2\pi}{T}\right)^2 = \frac{\Delta^2 y_i}{\Delta x_i^2}/y_i$, the period of oscillation T can be determined in this case as:

$$T = \frac{2\pi}{\omega} = \frac{6{,}28}{1{,}1} = 5{,}7 \text{ seconds; and } \omega = 1{,}1 rad/s.$$

The amplitude of the oscillation process A is determined as follows: $y_i=A*\sin(1{,}1x)$. From Table №2 when x=0,63, we have 2,1337=Asin(1,1*0,63), and from this, we find that A=3,5. Therefore, our function looks as follows: $y=3{,}5\sin(1{,}1x)=3{,}5\sin\left(\frac{2\pi}{5.7}x\right)$. To verify the suitability of the model and demonstrate the consistency of the proposed method, the calculated and real data were compared.

Table №2.

Comparison of real and modeled data for the function $y=3{,}5\sin\left(\frac{2\pi}{5.7}x\right)$

x	Y	Δy	Δy/ωΔx	Δ²y	Δ²y/ωΔx²	(Δ²y/ω Δx²)/y	Ya	Ya-Yc
0,0350	0,1318	0,1316	2,9932	-0,0116	-0,2634	-1,9977	0,1347	0,0029
0,0700	0,2634	0,1311	2,9817	-0,0173	-0,3944	-1,4973	0,2692	0,0058
0,1050	0,3945	0,1303	2,9643	-0,0231	-0,5247	-1,3301	0,4034	0,0089
0,1400	0,5248	0,1293	2,9413	-0,0287	-0,6540	-1,2462	0,5369	0,0121
0,1750	0,6541	0,1280	2,9125	-0,0344	-0,7820	-1,1955	0,6696	0,0155
0,2100	0,7821	0,1265	2,8781	-0,0399	-0,9085	-1,1616	0,8013	0,0192
0,2450	0,9087	0,1248	2,8382	-0,0454	-1,0333	-1,1371	0,9319	0,0232
0,2800	1,0334	0,1228	2,7928	-0,0508	-1,1560	-1,1186	1,0610	0,0276
0,3150	1,1562	0,1205	2,7419	-0,0561	-1,2765	-1,1041	1,1886	0,0324
0,3500	1,2767	0,1181	2,6858	-0,0613	-1,3946	-1,0923	1,3145	0,0377
0,3850	1,3948	0,1154	2,6245	-0,0664	-1,5099	-1,0825	1,4383	0,0435
0,4200	1,5102	0,1125	2,5582	-0,0713	-1,6224	-1,0743	1,5601	0,0499
0,4550	1,6226	0,1093	2,4868	-0,0761	-1,7317	-1,0672	1,6795	0,0569
0,4900	1,7320	0,1060	2,4107	-0,0808	-1,8376	-1,0610	1,7965	0,0645
0,5250	1,8379	0,1024	2,3299	-0,0853	-1,9400	-1,0556	1,9108	0,0728
0,5600	1,9404	0,0987	2,2446	-0,0896	-2,0387	-1,0507	2,0222	0,0819
0,5950	2,0390	0,0947	2,1550	-0,0938	-2,1334	-1,0463	2,1307	0,0916
0,6300	2,1338	0,0906	2,0612	-0,0978	-2,2240	-1,0423	2,2360	0,1022
0,6650	2,2244	0,0863	1,9635	-0,1016	-2,3103	-1,0386	2,3380	0,1136
0,7000	2,3107	0,0818	1,8619	-0,1052	-2,3922	-1,0353	2,4365	0,1258
0,7350	2,3925	0,0772	1,7567	-0,1086	-2,4694	-1,0321	2,5314	0,1388
0,7700	2,4698	0,0725	1,6482	-0,1117	-2,5418	-1,0292	2,6225	0,1528
0,8050	2,5422	0,0675	1,5365	-0,1147	-2,6093	-1,0264	2,7098	0,1676
0,8400	2,6098	0,0625	1,4217	-0,1175	-2,6718	-1,0238	2,7931	0,1833
0,8750	2,6723	0,0573	1,3043	-0,1200	-2,7292	-1,0213	2,8722	0,1999
0,9100	2,7296	0,0521	1,1843	-0,1223	-2,7812	-1,0189	2,9470	0,2174
0,9450	2,7817	0,0467	1,0621	-0,1243	-2,8279	-1,0166	3,0175	0,2359
0,9800	2,8283	0,0412	0,9377					
1,0150	2,8696							

In the table, the values of x_i are spaced at equal intervals of 0.035, so $\Delta x_i=\Delta x=0{,}035$, and $\Delta x_i^2 = \Delta x^2 = 0{,}01225$. Table №2 presents the results of the calculation of the average values, $|y_c - y_a| = 0{,}0845$.

Thus, we can draw the following conclusions:

1. If the results of the experiments are known, i.e., the values of x_i and y_i, $i = \overline{1, N}$, then it is possible to determine whether the dependence $y = f(x)$ is harmonic or not.
2. To determine the harmonicity of the function $y = f(x)$, we calculate the finite difference $\frac{\Delta^2 y}{\Delta x^2}$ and its ratio to y: if $\frac{\Delta^2 y}{\Delta x^2}/y = cont = \omega^2$, then the studied dependence is harmonic, i.e., it has the following form:

$$y = A\sin\frac{2\pi x}{T} + B\cos\frac{2\pi x}{T}.$$

3. One of the advantages of this method is that, knowing only the values of x_i and y_i, where $i = \overline{1, N}$, we can determine both the oscillation period T and the oscillation amplitudes A and B;
4. The amplitudes A and B are determined based on the solution of the second-order differential equation, which has the form: $y'' = -\omega^2 y$. In this case, the characteristic equation $к^2 = -\omega$ has an imaginary solution. Therefore, the general solution of the differential equation is: $y = A\sin\sqrt{\omega}t + B\cos\sqrt{\omega}t$.

The coefficients of this function are determined based on the initial conditions $y(x_0) = y_0$ and $y'^{(x_0)} = y_0'$. From these initial conditions, we obtain a system of two equations with two unknowns, and by solving this system, we find the coefficients A and B.

To verify this theory in practice, let's consider specific data on cotton yield in the period from 1991 to 2023 in the Bukhara region of the Republic of Uzbekistan. Back in the late 20th century, M.A. Abdullayeva proved the existence of cyclicality in cotton yields, the results of which were published in the 1982-1984 period in the journal “Хлопководство” (Cotton Cultivation). The author proposed a yield graph over an extended period based on a specific cyclicity.

Based on this evidence, we propose the most advanced methodology for determining these cycles. Here, $\Delta t_i = 1$.

Table №3 Table of calculations for determining the oscillation cycles of cotton yield in the Bukhara region of the Republic of Uzbekistan.

t	y_i	$k_i = y_i - 25{,}8$	$\frac{\Delta к_i}{\Delta t_i}$	$\frac{\Delta^2 к_i}{\Delta t_i^2}$	$\frac{\Delta^2 к_i}{\Delta t_i^2}/ki = \omega_i^2$
1.	34,00	8,20	-2,00000	4,90000	0,59756
2.	32,00	6,20	2,90000	-5,60000	-0,90323
3.	34,90	9,10	-2,70000	3,90000	0,42857
4.	32,20	6,40	1,20000	-6,00000	-0,93750
5.	33,40	7,60	-4,80000	5,50000	0,72368
6.	28,60	2,80	0,70000	-0,50000	-0,17857
7.	29,30	3,50	0,20000	1,60000	0,45714
8.	29,50	3,70	1,80000	-5,80000	-1,56757
9.	31,30	5,50	-4,00000	3,80000	0,69091

10.	27,30	1,50	-0,20000	1,30000	0,86667
11.	27,10	1,30	1,10000	0,00000	0,00000
12.	28,20	2,40	1,10000	0,20000	0,08333
13.	29,30	3,50	1,30000	-1,00226	-0,28636
14.	30,60	4,80	0,29774	-1,77444	-0,36968
15.	30,90	5,10	-1,47670	2,34451	0,45991
16.	29,42	3,62	0,86780	-5,35104	-1,47777
17.	30,29	4,49	-4,48324	7,27765	1,62128
18.	25,81	0,01	2,79441	-0,40895	0,00000
19.	28,60	2,80	2,38546	-0,77092	-0,27533
20.	30,99	5,19	1,61454	-2,71454	-0,52349
21.	32,60	6,80	-1,10000	1,00000	0,14706
22.	31,50	5,70	-0,10000	0,00000	0,00000
23.	31,40	5,60	-0,10000	1,40000	0,25000
24.	31,30	5,50	1,30000	-3,70000	-0,67273
25.	32,60	6,80	-2,40000	1,50000	0,22059
26.	30,20	4,40	-0,90000	-0,10000	-0,02273
27.	29,30	3,50	-1,00000	2,80000	0,80000
28.	28,30	2,50	1,80000	-4,20000	-1,68000
29.	30,10	4,30	-2,40000	11,30000	2,62791
30.	27,70	1,90	8,90000	-17,90000	-9,42105
31.	36,60	10,80	-9,00000		
32.	27,60	1,80			
				average	-0,27805
				ω	0,52730
				T	11,90963

In Table №3, the necessary calculations and data are provided, based on which the existence of oscillation cycles of cotton yield is determined for the Bukhara region of the Republic of Uzbekistan. The second column contains data on cotton yield for the period from 1991 to 2023. In the third column, the data is normalized as $k_i = y_i - y_{min} = y_i - 25{,}8$. The fourth and fifth columns show the data $\frac{\Delta \kappa_i}{\Delta t_i}$ and $\frac{\Delta^2 \kappa_i}{\Delta t_i^2}$, respectively. And the last column presents the value $\omega^2 = \frac{\Delta \kappa^2}{\Delta t^2}/y$. In Table №3, 85% of the data are always less than one in absolute value. Therefore, the average value of $|\omega_i^2|$ is taken as $|\omega_i^2| = 0{,}27805$ and ω=0,5273. Since $\frac{2\pi}{\mathrm{T}} = \omega$, in this case, we find that $\mathrm{T} = \frac{2\pi}{\omega} = \frac{6{,}28}{0{,}5273} = 11{,}9$.

In works dedicated to determining the oscillation cycles of agricultural crop yields, cycles are determined by comparing a large amount of data over an extended period of time. However, using the proposed method, it is possible to quickly determine the cyclicity of the process, even with minimal observations. The period T and the amplitude of oscillation A can also be determined.

Based on simple mathematical calculations, the amplitudes of oscillation can be determined. As is known, A and B are determined taking into account the initial conditions. Therefore, we have:

$$\begin{cases} y = Asin\omega t + Bcos\omega t \\ y' = A\omega sin\omega t \ - \ B\omega cos\omega t \end{cases}$$

Based on the initial conditions, we have:

$$\begin{cases} 8 = 0{,}48A + \ 0{,}88\ B \\ -2 = 0{,}52 * 0{,}88A \ - \ 0{,}52 * 0{,}48\ B \end{cases}$$

$$\begin{cases} -2 = 0{,}45A - 0{,}23B \\ 8 = 0{,}48A + 0{,}88B \end{cases}$$

$$\begin{cases} -4{,}44 = A \ - \ 0{,}5B \\ 16{,}6 = A + 1{,}83\ B \end{cases}$$

21,04 = 0 + 2,33B

B=9

A=-4,44+0,5B=-4,44+4,5≈0, so B=9; A=0. Therefore, y=9cos 0,51t

Therefore, the oscillatory process has the following form: $y = f(t) + E(t)$, where f(t) shows the general trend of yield growth, and E(t represents the influence of the external environment (noise). In our case, $E(t) = Acos\frac{2\pi t}{T} = 4{,}4\cos\frac{2\pi t}{12}$; f(t)=0.0122t² – 0.4328t+33,246, so

$$y=0.0122t^2-0.4328t+33{,}246+9\cos\frac{2\pi t}{12}.$$

Table №4

Comparison of actual and calculated cotton yield values, taking into account the cyclic oscillations.

years-	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Y_a	34,0	32,0	34,9	32,2	33,4	28,6	29,3	29,5	31,3	27,3	27,1
Y_c	34,7	31,3	33,9	30,6	33,2	29,9	32,6	29,3	32,1	28,8	31,6
$Y_a - Y_c$	-0,7	0,7	1,0	1,6	0,2	-1,3	-3,3	0,2	-0,8	-1,5	-4,5

years	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Y_a	28,2	29,3	30,6	30,9	29,4	30,3	25,8	28,6	31,0	32,6
Y_c	28,5	31,3	28,2	31,1	28	30,9	27,9	30,9	27,9	31
$Y_a - Y_c$	-0,3	-2,0	2,4	-0,2	1,4	-0,7	-2,1	-2,3	3,1	1,6

years	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Y_a	31,5	31,4	31,3	32,6	30,2	29,3	28,3	30,1	27,7	33,7	36,6	27,6
Y_c	28	31,1	28,2	31,4	28,5	31,7	28,9	32,2	29,5	32,7	30	33,4
Y_a - Y_c	3,5	0,3	3,1	1,2	1,7	-2,4	-0,6	-2,1	-1,8	1,0	6,6	-5,8

Let's consider the actual and calculated cotton yield values on the graph.

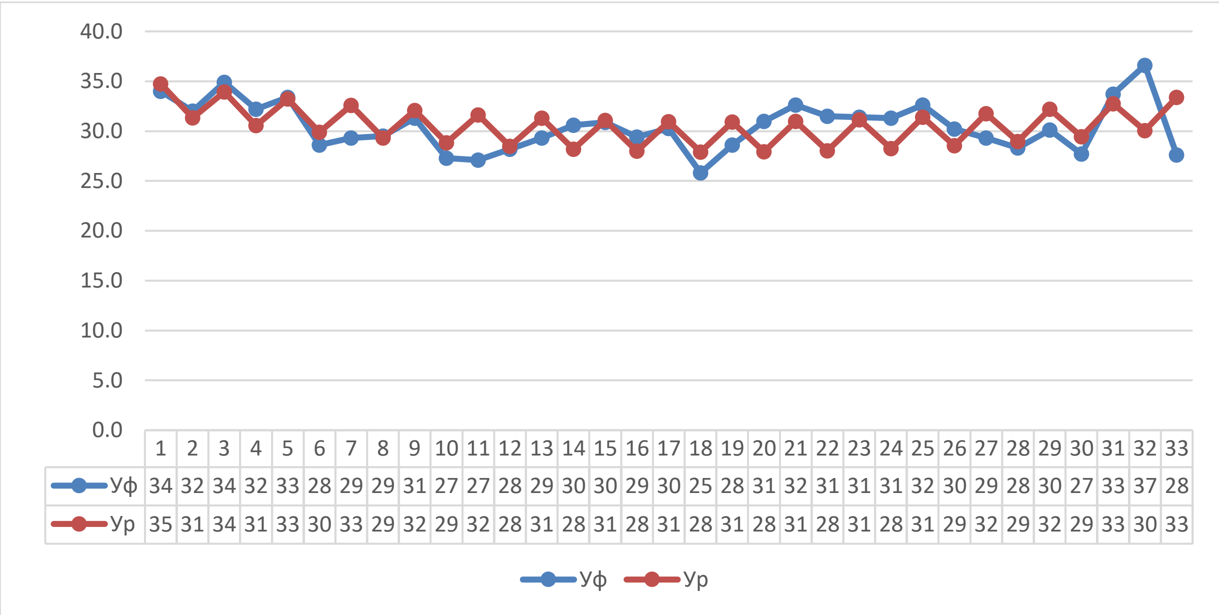

Figure 2. Graphical comparison of actual and calculated cotton yield values in the Bukhara region.

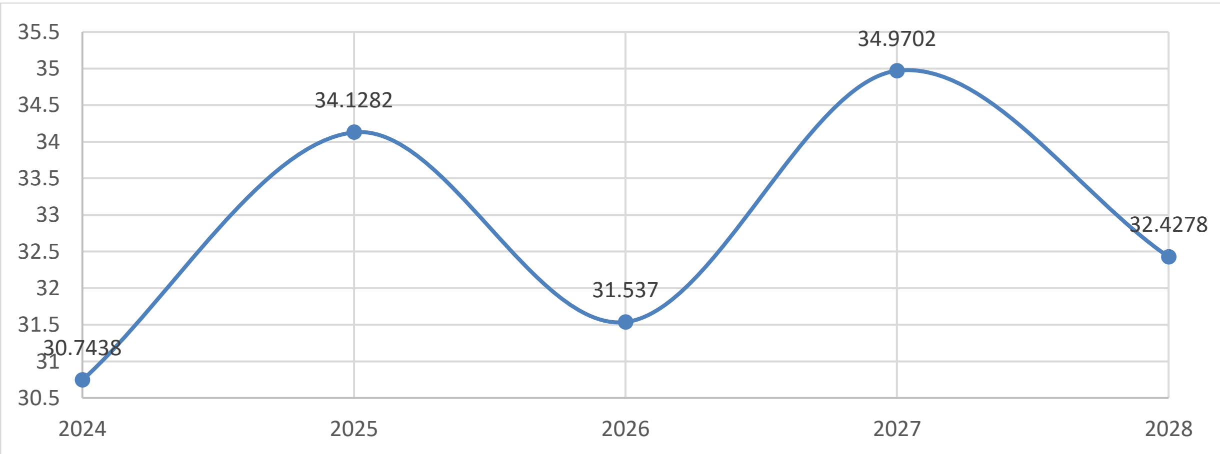

Figure 3. Graphical forecast of cotton yield considering fluctuations.

It can be seen that the cyclical nature in forecasting ensures reliable results.

Conclusion

Thus, the following results were obtained in this article:

1. If experimental data characterizing the state of the object at points x_i in the form of y_i, are available, it is possible to determine whether the process is harmonic or non-harmonic. The necessary condition for harmonicity is: $\frac{\Delta^2 y}{\Delta x^2}/y = -\omega^2 = \pm A$. If A> 0, the process is an oscillatory process.
2. When the value of $\omega = \frac{2\pi}{T}$ is known, the period of oscillation $\boldsymbol{T}$ is automatically determined as $T = \frac{2\pi}{\omega}$, and the frequency of oscillation $y = \frac{1}{T}$
3. If A<0, then the general solution of the equation and the desired dependency is a harmonic function: $y = Asin\sqrt{\omega}x + Bcos\sqrt{\omega}x$.
4. When A>0 , this process is not harmonic and has the following form: $y = Ae^{x} + Be^{-x}$
5. In any case, the coefficients A and of the harmonic function are determined based on the initial conditions $y(x_0) = y_0$ and $y'(x_0) = y_0'$; In this case, a system of two equations with two unknowns is solved, and the coefficients A and B are determined.
6. The method was tested based on a specific example, resulting in the determination of the suitability of the presented algorithm for solving the given problem.

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