DEVELOPMENT AND INVESTIGATION OF ALGORITHM FOR THE SYNTHESIS OF AN AUTOMATIC CONTROL SYSTEM OF THE DRYING PROCESS

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Abstract: At the first stage of research, the experimental transmission functions and optimal two-channel automatic adjustment system (ARS) of the residual moisture content during convection drying of apples were developed. As a result of the analysis of the structural synthesis of the ARS, the advantage of the optimal dual-channel ARS compared to the single-channel system was established. At the second stage of research, with a view to improving the quality of the single-channel speed ARS of the residual moisture content of apples, the robust ARS was developed by the method of parametric synthesis and root hodograph. Based on the research, the advantages of the speed single-channel robust system compared to the dual-channel system were established, which will significantly improve the quality of the products and reduce energy consumption for drying.

Key words: drying, optimization, dual-channel system, root hodograph, robust.

1. INTRODUCTION

In general, technological process of drying accounts for 30% of total energy consumption in the food industry. Therefore, the issues of optimal control of the drying process have always been attached great importance in order to improve energy saving and product quality. The basic requirements for the implementation of the drying process are to reduce energy consumption, to achieve the highest possible productivity and to reach the standard value of residual (final) moisture of the dried product at the outlet of the drying machine (10-12% for apples), which determines the shelf life of the dried product. The control of residual moisture of the product is very important, since over drying brings substantial wastage of energy and lower quality, while not proper drying leads to microbiological spoilage of the product, which is why the question of synthesis of an automatic control system of the fruit drying process does not lose its relevance [1,2,3,4]

The aim of the research in paper [5] is to evaluate the physic-chemical parameters of the drying process of apples and apricots using the experimental-industrial drying device. The device provides temperature control of the drying agent or adjustment of the flow rate.

The paper [6] offers a structure of an adaptive control system with an identifier based on robust and optimal controllers and a fuzzy inference unit. To reveal the contents of the latter, there is given a fragment of the decision tree on the choice of the controller structure. The analysis of the study results does not reflect the effectiveness of the proposed method.

In papers [7], the authors present the latest methods of quality control of fruit and vegetables drying process. The focus is on the implementation of sensors based on modern technologies in the online process. This is a necessary step to transform a conventional dryer into a smart dryer, which is the surer path to the production of high-quality dried fruits and vegetables.

Based on the analysis of scientific works on the presented topics, to ensure the optimal mode of the fruit drying process, and with a view to improving the quality of the control systems, the experimental transmission functions of the convection drying of apples have been developed. For the first time, the dual-channel ARS has been developed, and based on structural synthesis, its advantage has been established over the existing single-channel systems.

To improve the quality indicators of the existing single-channel control systems of residual moisture content of fruits, a robust ARS has been developed for the first time based on parametric synthesis using the root hodograph method.

The scientific novelty of the work lies in the development of optimal dual-channel and single-channel robust ARSs of the residual moisture content of fruits during convective drying, by means of structural and parametric synthesis.

The research goal of the paper is to develop the dual-channel and single-channel robust ARSs of fruit residual moisture content in the process of convective drying that provide the minimum energy consumption for drying and the achievement of the value specified in standard of the residual moisture content, hence the improvement of product quality.

2. MATERIALS AND METHODS

Generally, convection drying is the process of removing moisture from a product by means of heat and air circulation. The process of convective drying of fruits is characterized by two periods: the period of constant drying rate (I-period), when the moisture content of the product decreases intensively according to the linear law. This decrease in moisture content occurs up to the critical moisture value W_{cr}, after which the period of decreasing drying rate begins (period II). At the end of the second period, the moisture content of the product asymptotically approaches the equilibrium moisture content [3].

Convective drying of chopped apples starts with heating at 70 °C – 85 °C, when about 2/3 of the water evaporates, the temperature decreases to 50 °C – 55 °C. The entire drying process lasts 6-10 hours, and the dried apples are yellowish-brown in color, which must contain the final residual moisture content specified in the standard [1,2,3].

In the conveyor-type and tunnel-type dehydrators, the method of convective drying of fruits and vegetables is used, where the final residual moisture is automatically regulated by changing the temperature of the drying agent or the speed of movement of the product (or the blowing rate of the hot air flow on the material) through the appropriate regulatory bodies. In the first case, due to the large heat capacity of dehydrator, the ARS is inertial, while in the second case, the ARS is characterized by large accelerations. In both cases, the above-mentioned adverse circumstances lead to a decrease in product quality and an increase in energy consumption for drying. The main requirement for drying process optimization is to minimize the consumed energy and reach the standard value of the final moisture content of the product [3,8].

Based on the above, the existing ARSs of residual moisture of the product at the outlet of the drying apparatus has certain shortcomings due to the complexity and specificity of the technological process of drying, in particular they cannot ensure the conduct of the process in an optimal mode and therefore cannot meet requirements for product quality. Thus, we are suggesting the better justified versions of the ARSs of residual moisture of fruits.

3. RESULTS AND DISCUSSION

3.1. Structural synthesis of the dual-channel ARS of residue moisture of fruits

Figure 1 illustrates a computer model of the dual-channel ARS of residual moisture of fruits, which takes into account the possibility of simultaneous influence on the amount of residual moisture, with both speed and a thermal channels, where w_{set} is the standard assigned value residual moisture of fruit; $w(s)$- is the current value of change in the residual moisture of fruit; $E(S)$ - residual moisture and regulation error; $N(S)$ - disturbing effect; $W_{rv}(S)$, $W_{rQ}(S)$ - are the transfer functions of the regulators of the speed and heat channels; $W_v(S)$, $W_Q(S)$ - the transfer functions of the object, with the speed and heat channels, respectively.

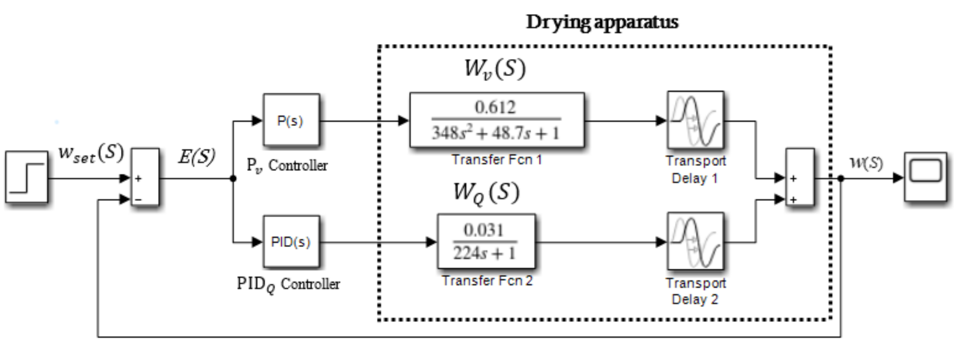


Figure 1. A computer model of the dual-channel ARS of residual moisture of fruits

In order to assess the quality of transient characteristics in the locked ARS, let us use the following criterion [9]:

$$J = \int_0^{\tau} e^2(\tau)d\tau \to min, \quad (1)$$

where $e(\tau) = w(\tau) - w_{set}$ – the regulation error of residual moisture of fruit,%; $w(\tau)$ – the current value of residual moisture of fruit, % and w_{set} - the standard assigned value residual moisture of fruit, %.

According to (1), one of the main requirements is the minimization of the established error value of the regulation, that is one of the speed r_v and thermal r_Q regulators must be of PI or PID type, since only in this case the astaticism of the closed system is ensured [10].

Assume that the r_v regulator of the speed channel is of a P_v - type, it is not difficult to show that the regulating effect at this time is of impulse nature. Since there is a relationship $\tau_v << \tau_Q$ between the delay times of the object's speed and thermal channels, then, under disturbance, the regulation is generated only in the speed channel, and the regulatory effect does not affect the course of the regulation process. On the other hand, it is clear that the regulatory effect $v(\tau)$ tends to zero when $\tau \to +\infty$, since the astaticism of the system is ensured by the regulator r_Q of the thermal channel. So, the impact will have a damping impulse characteristic when $\tau \to +\infty$ [10,11].

The main idea of the dual-channel ARS operation algorithm consists in using the thermal channel as a corrective effect. In order to form the initial stage of the transition process, when the thermal effect does not affect the regulation value, a significant delay of the drying device with a thermal channel is taken into account. Later, when the time of the transition process becomes equal to the delay time of the thermal channel, change in the regulatory effect through the speed channel will gradually stop, and the function of forming the regulatory effect is transferred to the thermal channel. In the frequency domain, this means that the low-frequency components of the disturbing effect are compensated up to the frequency of $\omega = 0$ in the thermal channel, and the high-frequency components are compensated in the speed channel.

To assess the capacity of the dual-channel ARS that we developed, we should consider the issue of optimal system debugging taking into account the criterion (1).

It is known that the quadratic integral criterion (1) of the regulation error of both single-channel and dual-channel systems (with the P_v and PI_Q or PID_Q regulators) is directly proportional to the ratio of K_r/T_r when the frequency band of the disturbing effect is bounded above by the cut-off frequency ω_c since $\omega_c << \omega_r$, where ω_r is the resonant frequency of the locked system ($|\Phi(j\omega)|$ - maximum point) [10,12].

The problem of searching for the optimal parameters of a dual-channel system by criterion (1), similarly to single-channel systems, taking into account the limitation on the admissible stability margin of the closed system

$$M = \max_{\omega \geq 0} |\Phi(j\omega)| \leq 1{,}4, \quad (2)$$

where M is variability, and $|\Phi(j\omega)|$ is the modulus of the amplitude-phase-frequency characteristic of the closed system, can be written as follows [11]:

$$\{K_{rQ}/T_{rQ}\} \to max. \quad (3)$$

Thus, in order to assess the quality of regulation in the dual-channel ARS, we investigated the effect of the value of the coefficient K_{rv} on a range of change in the parameter $\{K_{rQ}/T_{rQ}\}$ using the iteration method.

When solving the problem of optimal regulation of the drying apparatus, along with the above-mentioned conditions (1)–(3), we must take into account the technological limitations

$$T_{min} \leq T(t) \leq T_{max}\ , \quad t_0 \leq t \leq t_F\ , \tag{4}$$

$$v_{min} \leq v(t) \leq v_{max}\ , \quad t_0 \leq t \leq t_F\ , \tag{5}$$

where T – is the product temperature (°C), and υ - It is the speed of movement of hot air flow or conveyor (m/sec), during which the desired characteristics determining the quality of the product are achieved [12]. Technological restrictions are not imposed on the regulatory effects, but on the intermediate phase variables of the object. The regulating effect of the speed channel is the voltage $u(\tau)$ at the inlet of the drive control scheme of the dehydrator's conveyor (or fan), and the temperature regulation is done by changing the position of the regulatory valve on the steam supply line, which causes instantaneous changes in the steam pressure $P(\tau)$.

The basic parameters of the drying process are adversely affected not only by the maximum deviation of the speed $\Delta v_m(\tau)$ from the nominal value, but also by the instability of the speed during the entire transition process. This adverse circumstance when solving the problem of optimal synthesis of the system is taken into account along with the quadratic integral value (1) of the regulation error, based on the comparative analysis of different versions of the ARSs. In addition, in the paper, as the quality assessment criteria of the transition characteristics of the ARSs are used:

over-regulation (%),

$$\sigma = max\,|\,e(\tau)/w_{set}| \tag{6}$$

and regulation time (sec) [13,15],

$$T_s = min\{T: |e(\tau)/w_{set}| < 0{,}05, \quad \tau > T\}\ . \tag{7}$$

From the experimental dynamic curves of convective drying of apples using the least squares numerical method, we developed transfer functions with respectively, the speed

$$W_v(S) = \frac{0{,}612}{348s^2+48.7s+1} \cdot e^{-14s}, \tag{8}$$

and thermal

$$W_Q(S) = \frac{0{,}031}{224s+1} \cdot e^{-55s} \tag{9}$$

channels [3]. The parameters of the regulators of the dual-channel ARS that we developed P_v ($K_p = 4{,}01$), PID_Q ($K_p = 75{,}54$; $K_I = 0{,}01$; $K_D = 23{,}3$) and of single-channel ARSs of the existing speed channel PID ($K_p = 4{,}75$; $K_I = 0{,}11$; $K_D = 43{,}22$) and the thermal channel PI ($K_p = 64{,}6$; $K_I = 0{,}31$), taking into account the stability condition of the systems, have been determined using the *pidtune* function of the Matlab system and by automatic setting the PID regulator block of the *Simulink* software Control System Toolbox package in real-time [13].

Based on the analysis of the research results, the advantage of the optimal dual-channel ARS developed by the structural synthesis over the single-channel ARS has been established, which can be clearly seen from the analysis of the transition characteristics shown in Figure 2 and quality indicators of the ARSs presented in Table 1.

Table 1. Quality indicators of the ARSs of residual moisture of apples

Automatic regulation system (ARS)	***System's quality indicators***	
	T_s, sec	*σ, %*
With a speed channel	*114*	*32,6*
With a thermal channel	*382*	*5,59*
With a dual-channel (speed and thermal channels)	*120*	*6,66*

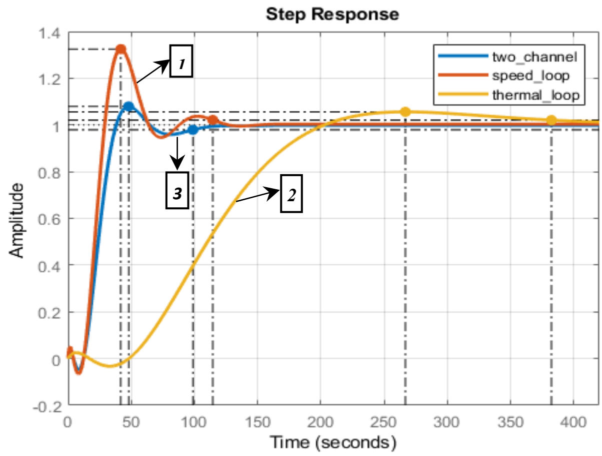


Figure 2. The transition characteristics of the optimal dual-channel ARS of residual moisture of apples: 1 – with a speed channel, 2 – with a thermal channel, 3 – with a dual-channel (speed and thermal channels)

3.2. Parametric synthesis of the speed single-channel ARS of residual moisture of fruits

As the drying process occurs in the face of significant uncertainty, the practical implementation of the dual-channel ARS of residual moisture of apple that we developed is complicated and requires additional financial costs. At the same time, the analysis of the research results and the classical methods of synthesis, in order to further possible improvement of the quality of the ARS and, accordingly, the quality of the dried fruit, leads to the need to develop the speed single-channel robust ARS, which provides the required quality of the system, regardless of changes in a large range of model parameters and errors, due to the low sensitivity of the robust system [14,15].

The goal of the synthesis of the single-channel speed ARS (Figure 3) of residual moisture content of fruits is to select such K_p, K_I and K_d parameters of the PID-regulator that would meet the quality requirements of the system and ensure its robustness. Unfortunately, the question of how the regulator parameters should be selected so that the system is robust cannot be answered immediately. We select the parameters of the regulator by the iteration method, and if necessary, the robustness of the system can be checked by means of simulation modeling.

The general structure of the drying process control system, in which potential uncertainties are included, is shown in Figure 3. The given model takes into account *N(S)* - sensor noise, *F(S)* - disturbance, $W_v(S)$ - drying apparatus with speed channel with the unforeseen dynamic parameters that are measurable, regulator and the correction device. These factors are important, it is therefore essential that the developed system should maintain the required quality of regulation [10,13].

Let us represent the transfer function of the drying device by the speed channel (8) with the robustness parameter c_0 [15]:

$$W_{vc_0}(S) = \frac{0,612}{348s^2+48.7sc_0+c_0^2} e^{-14s} \ , \tag{10}$$

which we should include in the robustness control system shown in Figure 3.

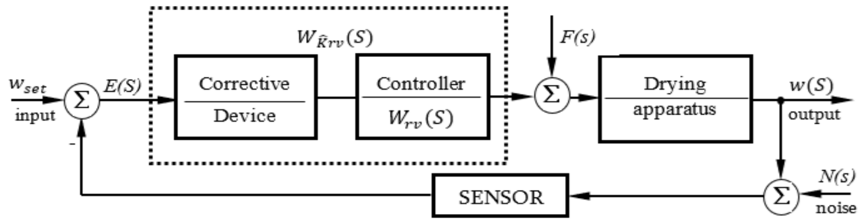


Figure 3. The robust control system of the process of drying with a correction device

We carried out the synthesis of system regulation when the nominal value of the robustness parameter c_0 is equal to 1 ($c_0 = 1$). Achieving the system quality requirement can be ensured by introducing a correction device into the control loop.

The relative stability and quality of the considered speed single-channel ARS is directly related to the location of the roots of the characteristic equation on the *s*-plane. It is also possible to obtain the desired quality indicators of the locked ARS by judicious selection of one or more parameters of the system. Therefore, it is interesting to study how the roots of the characteristic equation on the *s*-plane are shifted when any parameter of the system changes. The location of the roots of the system on the *s*-plane can be determined graphically, by the so-called root hodograph method that is an effective tool in the analysis and synthesis of ARS [11,15].

The characteristic equation of a single-channel speed ARS takes on the following form:

The characteristic equation of a single-channel speed ARS takes on the following form:

$$1 + \hat{K} W_{v \cdot op}(s) = 1 + \hat{K} \frac{p(s)}{q(s)}, \tag{11}$$

where

$$W_{v \cdot op}(s) = \frac{0.07597\, s^4 - 0.02421\, s^3 + 0.00127\, s^2 + 0.0004263\, \mathrm{s} + 1.217\mathrm{e}{-05}}{s^5 + 0.5685\, s^4 + 0.1241\, s^3 + 0.009799 s^2 + 0.0001759\, \mathrm{s}} \tag{12}$$

– is the Laplace transform of the delay time of the object’s transfer function (10), which is approximated by the rational transfer function *pade* of the Matlab software; from $\hat{K}$ - 0 to ∞ is the variable amplification coefficient of the uncorrected system; p(s) და q(s) are polynomials relative to variable *s* [13].

Figure 4 illustrates the characteristic hodograph of the roots of equation (11) of the single-channel speed ARS of residual moisture of apples, for the construction of which and subsequent selection of the roots, the *rlocus* and *rlocfind* functions of the Matlab program have been used [11,12,15].

After that, it is possible, based on the analysis of the root hodograph, to impose the following requirements on the robust ARS to be developed:

1. System regulation time (with a 5% criterion) T_s<145 sec and over-regulation $\sigma < 6$ %;
2. The poles $s = -\xi\omega_n = -0{,}0274$ ($T_s = 4/\xi\omega_n$) of the characteristic equation of the transfer function $W_{v \cdot op}(s)$ should be located to the left of the vertical line represented on the root hodograph (Figure 4), where $\xi = 0{,}825$ - is the corresponding damping coefficient of the selected pole, and $\omega_n = 0{,}0333$ is the natural frequency.

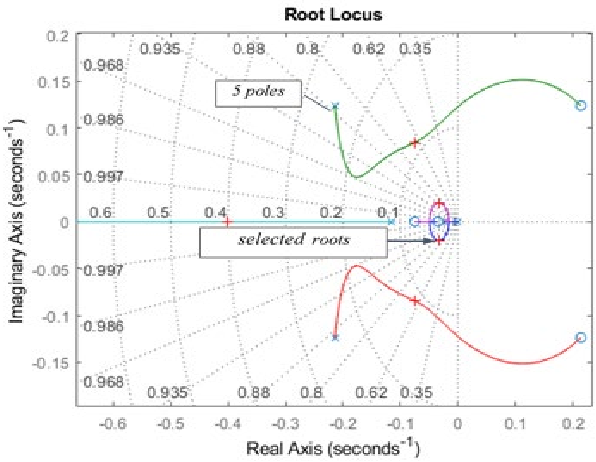


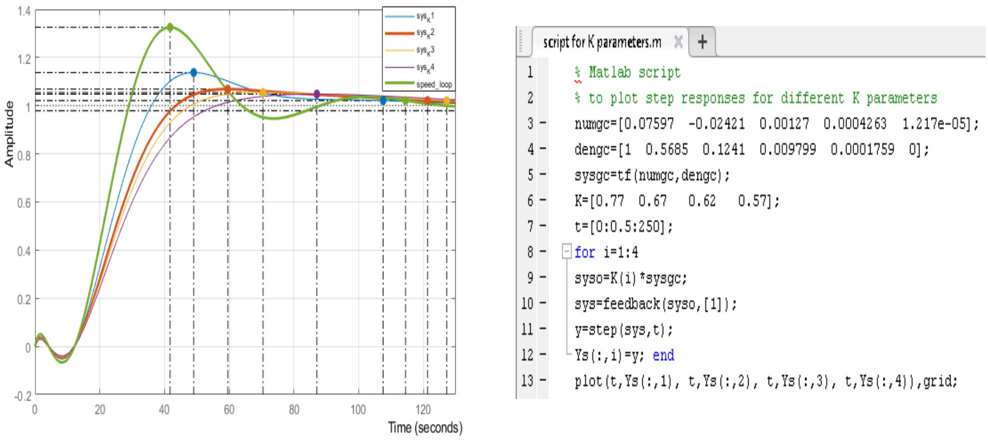
Figure 4. The root hodograph of the single-channel ARS of residual moisture of apples

On the root hodograph of the single-channel ARS of the apple drying process (Figure 4), we select the desired location of the roots in the appropriate region and find the value of the parameter $s = -0{,}0363 + 0{,}108i$ at the pole time using the *rlocfind* function [13,15].

In order to meet the requirement for re-adjustment of the single-channel speed ARS of residual moisture of apples ($\sigma < 6$ %), we should include a correction device with the amplification coefficient $\widehat{K}$ in the system the PID- regulator (Figure 3), and find its value by the iteration method, with script written in the Matlab program [12,14]. The results of the study are shown in Figure 5 a, b and presented in Table 2, where the value of overshoot index required to the system - 5.43% corresponds to the value of the amplification coefficient of the correction device - $\widehat{K}$ = 0.62.

Table 2. Quality indicators of the single-channel speed ARS of residual moisture of apples for different values of the parameter $\widehat{K}$

$\widehat{K}$	0,57	0,62	0,66	0,77
T_s, sec	135	127	121	108
σ, %	4,82	5,43	6,87	13,8



a) b)

Figure 5. The characteristics of the single-channel speed ARS of residual moisture of apples: a) for different values of the parameter $\widehat{K}$; b) Matlab program script

The analysis of the transient characteristics of the single-channel speed ARS of residual moisture during convective drying of apples shows that the quality of the system is improved by varying the value of the parameter $\widehat{K}$ – in accordance with the requirements. Therefore, in order to include the coefficient $\widehat{K}$ in the system (see Figure 3), we insert a correction device, and the transfer function of the PID regulator will finally take on the following form:

$$W_{\widehat{K}rv}(S) = \widehat{K} \cdot \frac{K_d s^2 + K_p s + K_i}{s} = \widehat{K} \cdot \frac{42{,}2s^2 + 4{,}75s + 0{,}113}{s}. \quad (13)$$

The determined values of the parameter $\widehat{K}$ (according to variation) allowed to determine the range of change in the parameter c_0 of the system robustness by the iterative method and to construct the system robustness curves.

As a result of the robustness study, we determined that the construction of the transient characteristic of the ARS of residual moisture at the outlet of the drying apparatus is appropriate with with the regulator (13) $W_{\widehat{K}rv}(S)$, when the parameters of the drying apparatus change within the range of $0{,}6 \le c_0 \le 1{,}2$.

A MatLab program script (Figure 6) [12,14,15] was compiled to construct the transient characteristics of the single-channel speed ARS of residual moisture of apples, for specific parameter value c_0.

To make the program more interactive, the c_0 value was entered at the command-line level [15]. The results of the study are shown in Figure 7.

The simulation results show that the synthesized PID controller makes the system robust according to changes in the c_0 parameter. Figure 7 illustrates the effect of change in the robustness parameter c_0 on the single-channel speed ARS, from which it can be seen that the difference between the transient characteristics is less noticeable in the interval of $0.6 \le c_0 \le 1.2$, so the system does not need to be checked for robustness anymore, which is why we stop the system synthesis procedure.

As a result of the implementation of the Matlab program script shown in Figure 6, the transient characteristics obtained as (Figure 7) show that the synthesized corrective device ensures the robustness of the control system when the coefficient $\widehat{K}$ changes within the appropriate limits.

script for K parameters.m | robust system.m

```
% plot robust curves
c0=1.1;
numg=[0.612];
deng=[348 48.7*c0 c0^2];
sysg=tf(numg,deng);
%pade tf
[num,den]=pade(14,2);
d1=tf(num,den);
O=series(sysg,d1);
% K'*PID_tf
numgc=0.62*[43.2  4.75  0.113];
dengc=[1 0];
sysgc=tf(numgc,dengc);
syso=series(sysgc,O);
sys=feedback(syso,[1]);
% step response
step(sys)
```

Figure 6. A MatLab program script MatLab for specific parameter value C_0 of robustness

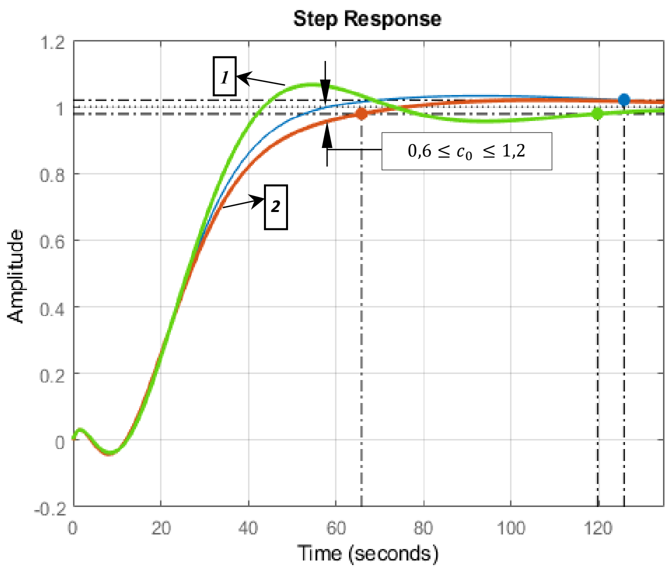


Figure 7. The transient characteristics of the ARS of residual moisture of apples:
1- dual-channel ARS; 2- single-channel robust ARS

Based on the analysis of the studies, the quality advantage of the robust speed single-channel ARS of residual moisture of apples was established, compared to quality indicators of the dual-channel ARS (Figure 7), which is clearly seen from the numerical values of quality indicators presented in Table 3.

Table 3. Quality indicators of the dual-system and single-channel robust ARSs of residual moisture of apples

Automatic regulation system (ARS)	***System's quality indicators***	
	T_s, sec	*σ, %*
Dual-channel (speed and thermal channels)	*120*	*6,66*
Robust channel (single-channel and speed)	*65,9*	*2,06*

Thus, the parametric synthesis algorithm of the single-channel speed ARS of the fruit drying apparatus developed in the paper, which is based on the robust expansion of the root hodograph, guarantees robust stability in case of any change within the given range of dynamic characteristics of the convective drying of apples.

4. CONCLUSION

In the paper, based on the analysis of the results of the optimal dual-channel ARS for residual moisture of fruits developed at the first stage of the research and the results of the structural synthesis, the advantage of the dual-channel ARS compared to the single-channel systems was established.

At the second stage of the research, with a view to further improving the quality of transient characteristic of the single-channel ARS of residual moisture of fruits, the developed dual-channel speed robust control system of the drying device ensures the stable automatic maintenance of the desired residual moisture of fruits with sufficient accuracy and, accordingly, the high quality of the products and the reduction of energy consumption for drying.

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