The study of variability of dynamic properties of the drying chamber of the grain dryer changing the technological parameters of drying

V G Zakhakhatnov, V M Popov and V A Afon'kina

Federal State Budgetary Educational Institution of Higher Education «South Ural State Agrarian University», 13, ul. Gagarina, Troitsk, Chelyabinsk Region, 457100, Russia

E-mail: zahvg@inbox.ru

Abstract. The complexity of identification of transfer-function of the drying chamber is connected with a great variety of grain crops, different drying modes of seed, food and feeding grain as well as thermolabile properties of wet material so that in the drying chamber there are grains with different stages of drying and as a consequence of this with different transfer functions. One of the forecasting methods of the dynamic processes of the drying chamber is based on the use of transfer functions of the drying chamber which were got based on the analysis of experimentally obtained transfer characteristics. This paper presents the results of processing of the transfer characteristics of the drying chamber which were got for different parameters of the technological process of drying – heat carrier temperature, grain initial moisture content, initial grain temperature. The transfer functions of the drying chamber for different parameters of the technological process of drying are obtained. For three exposure channels – heat carrier temperature-grain temperature, heat carrier temperature-grain moisture content, heat carrier temperature-worked out heat carrier temperature the variability of the dynamic properties of the drying chamber changing the technological parameters of drying is estimated. Qualitative assessments of inertial and frequency properties are obtained. A significant variability of the dynamic properties of the drying chamber was revealed, which was estimated by scattering of the PI controller settings when the object with the transfer functions under study was included in the automatic control system. The study is performed under the sponsorship of Russian Fundamental Research Fund and Chelyabinsk region as a part of the scientific project № 20-416-74001.

1. Introduction

To create an effective system of automatic control of the drying process it is necessary to describe the dynamic processes occurring in the drying chamber. In practice, identifying the transfer function of the drying chamber is a difficult task. This is due to a great variety of grain crops, different drying modes of seed, food and feeding grain as well as thermolabile properties of wet material so that in the drying chamber there are grains with different moisture content and temperature and as a consequence of this with different transfer functions [1-2].

Whereby process modeling occurring in the drying chamber during grain drying, two approaches are used. One is supposed the use of analytical equations derived from a theoretical analysis of the physics of the drying process [3-4] which describe heat-conduction and mass transfer processes in a thin bed of
grain. A complete picture of processes in the drying chamber may be provided due to calculations for several zones with different boundary conditions [5-6]. The practical use of this approach for the control system design of the technological process of drying is difficult due to the complexity of the used mathematical tools and the interpretation of the obtained results.

Another approach to the forecasting of the dynamic processes of the drying chamber is based on the use of transfer functions of the drying chamber which were obtained experimentally. The drying chamber is studied as a control object which is affected by controlling and disturbing factors. The authors of studies [7-10] note that due to the dependence of the thermophysical properties on the modes and position of the grain in the dryer, as well as uncontrolled random factors, the transfer functions are different for different drying zones. In studies carried out on a mine grain dryer [2], a significant change in the transmission coefficient on the channels "moisture → grain temperature" and "speed of grain movement → grain temperature" is noted.

In this regard, the purpose of the study is to identify the transfer functions of the drying chamber with a fixed bed of grain and to evaluate their variability changing the main technological parameters of drying - the initial moisture content of the grain, the temperature of the heat carrier and the initial temperature of the grain.

2. Materials and methods
The identification of the transfer function of the object can be made by the transient characteristic (step response). For a fixed bed of grain, which is found during drying in a chamber dryer, the factors affecting the technological process are the temperature and speed of the heat carrier, the initial temperature and the initial moisture content of the grain. The speed of the heat carrier can be established, as far as in the real dryers it is usually not regulated. The studies have been carried out at wheat drying in the fixed bed 200 mm thick on the test station [11]. The heat carrier speed has been kept constant at 0.5 m/s. The beginning of the drying process, when the difference between the temperature of the grain and the temperature of the heat carrier is significant, can be considered as a step effect. By registering the values of the current temperature and moisture content of the grain, as well as the temperature of the worked out heat carrier, it is possible to obtain transient characteristics through the control channels – the temperature of the heat carrier - the temperature of the grain, the temperature of the heat carrier - the moisture content of the grain and the temperature of the heat carrier - the temperature of the worked out heat carrier. To obtain transient characteristics in the range of variation of the technological parameters of drying, the values of the factors at the initial moment of drying were established according to the planning matrix of the 3-level Box-Behnken design. As factors, the temperature of the heat carrier $\theta_{hc}$, the temperature of the grain $\theta_c$ and the initial moisture content of the grain $W_c$ are taken. The initial moisture content varied between 18 ... 24 ... 30%, the initial grain temperature 10 ... 20 ... 30°C, the temperature of the heat carrier 60 ... 75 ... 90°C. Drying was carried out to a moisture content of 14% with registration of the parameters after 2 minutes. As a result of the experiments, 15 transient characteristics were obtained for different values of the temperature and moisture content of the grain and the temperature of the worked out heat carrier during the drying process according to the number of rows of the planning matrix.

3. Results and discussion
The identification of transfer functions for each matrix row of the plan has been carried out in Matlab, System Identification Toolbox. The result of identification in the category Transfer Function Identification in presented in table 1.
Table 1. The results of identification of the transfer functions of the drying chamber for various parameters of the technological process of drying.

| No | $W_c$ | $\theta_c$ | $\theta_{hc}$ | $\theta_{hc} \rightarrow \theta_{sp}$ | $\theta_{hc} \rightarrow \theta_c$ | $\theta_{hc} \rightarrow W_c$ |
|----|-------|------------|--------------|--------------------------------|------------------|------------------|
| 1  | 30    | 30         | 75           | $\frac{0.01009s + 0.04329s}{s + 0.0249}$ | $\frac{0.208s + 0.00676}{s^2 + 0.4485s + 0.01111}$ | $\frac{-0.01062}{s + 0.0296}$ |
| 2  | 30    | 10         | 75           | $\frac{0.03123s + 0.01948}{s + 0.0249}$ | $\frac{-0.3886s + 2.357}{s^2 + 26.9s + 4.15}$ | $\frac{-0.0074}{s + 0.019}$ |
| 3  | 18    | 30         | 75           | $\frac{-0.1275s + 0.1403}{s^2 + 1.368s + 0.438}$ | $\frac{0.2687s + 0.09126}{s^2 + 1.101s + 0.1912}$ | $\frac{-0.0098}{s + 0.09}$ |
| 4  | 18    | 10         | 75           | $\frac{0.02611s + 0.02991}{s + 3.316e - 11}$ | $\frac{0.1096s + 0.1616}{s + 0.2269}$ | $\frac{-0.0103}{s + 0.096}$ |
| 5  | 24    | 20         | 75           | $\frac{-0.1186s + 0.1357}{s^2 + 1.499s + 0.2648}$ | $\frac{0.1322s + 0.01348}{s^2 + 0.4812s + 0.01649}$ | $\frac{-0.0108}{s + 0.0439}$ |
| 6  | 30    | 20         | 90           | $\frac{-0.07874s + 0.1217}{s^2 + 2.221s + 0.2313}$ | $\frac{0.09891s + 0.0289}{s^2 + 0.5594s + 0.0418}$ | $\frac{-0.013}{s + 0.0459}$ |
| 7  | 30    | 20         | 60           | $\frac{-0.06074s + 0.03417}{s + 0.07051}$ | $\frac{0.1876s + 0.007612}{s^2 + 0.4438s + 0.0122}$ | $\frac{-0.008}{s + 0.0195}$ |
| 8  | 18    | 20         | 90           | $\frac{-0.008583s + 0.05627}{s + 2.034e - 11}$ | $\frac{0.03847s + 0.2142}{s + 0.4288}$ | $\frac{-0.0126}{s + 0.0157}$ |
| 9  | 18    | 20         | 60           | $\frac{-0.09882s + 0.0677}{s^2 + 1.504s + 0.3442}$ | $\frac{0.057s + 0.187}{s + 0.336}$ | $\frac{-0.008}{s + 0.068}$ |
| 10 | 24    | 20         | 75           | $\frac{-0.06436s + 0.03563}{s^2 + 0.7414s + 0.07338}$ | $\frac{-0.3886s + 2.357}{s^2 + 26.9s + 4.15}$ | $\frac{-0.00897}{s + 0.0326}$ |
| 11 | 24    | 30         | 90           | $\frac{-0.1926s + 0.263}{s^2 + 4.452s + 0.5738}$ | $\frac{0.1299s + 0.09026}{s^2 + 1.656s + 0.1755}$ | $\frac{-0.0104}{s + 0.0514}$ |
| 12 | 24    | 30         | 60           | $\frac{0.06742s + 0.08952}{s^2 + 1.302s + 0.2029}$ | $\frac{0.04108s + 0.0179}{s^2 + 0.6351s + 0.04312}$ | $\frac{-0.008}{s + 0.0289}$ |
| 13 | 24    | 10         | 90           | $\frac{0.06408s + 0.02688}{s + 0.02063}$ | $\frac{0.09391s + 0.07853}{s + 0.1273}$ | $\frac{-0.009}{s + 0.033}$ |
| 14 | 24    | 10         | 60           | $\frac{0.1656s + 0.001228}{s^2 + 0.3554s + 0.00000124}$ | $\frac{0.08175s + 0.03917}{s^2 + 0.6978s + 0.06113}$ | $\frac{-0.0106}{s + 0.04}$ |
| 15 | 24    | 20         | 75           | $\frac{-0.01261s - 0.00338}{s^2 + 0.4151s + 0.01186}$ | $\frac{0.1079s + 0.02291}{s^2 + 0.7152s + 0.03271}$ | $\frac{-0.012}{s + 0.055}$ |
The transfer functions in the channel $\theta_{hc} \rightarrow W_c$ appear as first-order lag. The sign "-" shows moisture reduction in process of time.

The transfer functions in the channel $\theta_{hc} \rightarrow \theta_c$ approximate by the transfer function of series-connected first-order lag and lead network – experiments 8, 9, 13 and series-connected second-order lag and lead network – experiments 1…7, 10…12, 14, 15.

In the channel $\theta_{hc} \rightarrow \theta_{sp}$, the transfer functions of experiments under numbers 1, 2, 4, 7, 8, 13 have the form of a series-connected first-order lag and lead network, in other experiments, the transfer functions have the form of a series-connected second-order lag and lead networks. The presence of the lead network in the transfer functions reflects the tendency for the grain temperature rise and the temperature of the worked out heat carrier to increase at the end of drying.

To analyze the frequency characteristics of transfer functions, given in the table 1, the Nyquist diagram has been constructed for each of them. Calculations show that the object with such transfer functions has a significant amplitude and phase stability margin.

To analyze the inertial characteristics of transfer functions in response to a single step signal, the rise time of the output signal has been taken. The results are presented in table 2.

**Table 2.** Output rise time (sec.) while signaling on the step action input.

| Experiment no | $\theta_{hc} \rightarrow \theta_{sp}$ | $\theta_{hc} \rightarrow \theta_c$ | $\theta_{hc} \rightarrow W_c$ |
|---------------|------------------------------------|---------------------------------|------------------------------|
| 1             | 7646                               | 2453                            | 7222                         |
| 2             | 7855                               | 1666                            | 7232                         |
| 3             | 619                                | 829                             | 2870                         |
| 4             | 4680                               | 1121                            | 2689                         |
| 5             | 1316                               | 5583                            | 5602                         |
| 6             | 2361                               | 2747                            | 5405                         |
| 7             | 3685                               | 3675                            | 7625                         |
| 8             | 367                                | 618                             | 8719                         |
| 9             | 983.5                              | 783                             | 3784                         |
| 10            | 2251                               | 1666                            | 6862                         |
| 11            | 1944                               | 2220                            | 4911                         |
| 12            | 1448                               | 3298                            | 7308                         |
| 13            | 1173                               | 1983                            | 6813                         |
| 14            | 1740                               | 2480                            | 6011                         |
| 15            | 1398                               | 4845                            | 4622                         |

Analysis of the inertial characteristics reveals that the rise time in the channels $\theta_{hc} \rightarrow \theta_{sp}$, $\theta_{hc} \rightarrow \theta_c$ and $\theta_{hc} \rightarrow W_c$ is within the intervals 2689…8719s, 616…3675s and 367…7855s, relative range of variability for this channels is 2.84, 2.07 and 1.0 respectively.

To assess the variability of the dynamic properties of the transfer functions as part of the automatic control system, the PI controller settings optimized in response to a step action for an overshoot of 1.11% and a peak value of 1.01 response were calculated in the Matlab program. The research design is presented in figure 1.

![Figure 1. The study of transfer functions.](image)
The calculated values of the controller settings - the gain of the proportional component P and the integral component I are given in table 3.

**Table 3.** Settings parameters of PI controller for different values of technological parameters of drying, identified for the transient process with parameters Overshoot=1.11% and Peak =1.01.

| No | Wc (%) | θc (°C) | θhc (°C) | θhc → θsp | θhc → θc | θhc → Wc |
|----|--------|---------|----------|------------|----------|---------|
|    |        |         |          | P          | I        | P       | I       |
| 1  | 30     | 30      | 75       | 3.5778     | 0.33151  | 2.8368  | 1.3581  | -4.7134 | -0.16832 |
| 2  | 30     | 10      | 75       | -7.6376    | -0.00194 | 1.6518  | 0.11469 | -4.342  | -0.09953 |
| 3  | 18     | 30      | 75       | 3.4208     | 0.88463  | 13.8285 | 10.4543 | -5.5304 | -1.6863  |
| 4  | 18     | 10      | 75       | 16.8177    | 0.24482  | 1.352   | 0.43964 | -16.599 | -1.5936  |
| 5  | 24     | 20      | 75       | 3.7491     | 0.57217  | 0.21022 | 0.0090852 | -6.874 | -0.36406 |
| 6  | 30     | 20      | 90       | 3.7624     | 0.45637  | 1.7913  | 0.21671 | -5.9567 | -0.33234 |
| 7  | 30     | 20      | 60       | 3.1519     | 0.3039   | 4.7598  | 0.23712 | -4.122  | -0.09697 |
| 8  | 18     | 20      | 90       | 19.3581    | 0.3388   | 2.4452  | 1.5702  | -2.1072 | -0.03991 |
| 9  | 18     | 20      | 60       | 0.40492    | 0.15621  | 2.1742  | 0.97147 | -4.4082 | -1.1731  |
| 10 | 24     | 20      | 75       | 4.0344     | 0.26766  | 3.0218  | 0.54276 | -6.146  | -0.24172 |
| 11 | 24     | 30      | 90       | 3.7239     | 0.55753  | 2.7704  | 0.4244  | -8.3182 | -0.52361 |
| 12 | 24     | 30      | 60       | 4.0397     | 0.855571 | 4.0529  | 0.38538 | -6.1091 | -0.213  |
| 13 | 24     | 10      | 90       | 1.9863     | 0.091528 | 1.5726  | 0.28631 | -6.2007 | -0.24686 |
| 14 | 24     | 10      | 60       | 0.000618   | 0.0      | 2.9615  | 0.376421 | -6.7644 | -0.32643 |
| 15 | 24     | 20      | 75       | -6.8161    | -0.25456 | -6.8161 | -0.25456 | -7.7325 | -0.51695 |

Table 4 shows the intervals of variation, mean values, standard deviations and variation coefficients of the PI controller settings for exposure channels under study.

**Table 4.** Relative range of variability \( \rho = \frac{x_{\text{max}} - x_{\text{min}}}{\bar{x}} \), mean values of \( \bar{x} \) parameter, standard deviation \( sd \) and variation coefficient \( \nu = sd/\bar{x} \) of parameters of PI controller settings.

| Exposure channel | \( \rho \) | \( \bar{x} \) | \( sd \) | \( \nu \) |
|------------------|-----------|------------|--------|--------|
| \( \theta_{hc} \rightarrow \theta_{sp} \) | 7.55      | 3.47       | 3.572  | 0.32   | 6.99   | 0.313  | 1.956  | 0.978  |
| \( \theta_{hc} \rightarrow \theta_c \)  | 5.29      | 9.37       | 2.574  | 1.142  | 4.07   | 2.621  | 1.581  | 2.295  |
| \( \theta_{hc} \rightarrow W_c \)       | 2.27      | 3.24       | -6.395 | -0.508 | 3.23   | 0.534  | 0.5    | 1.051  |
The data in table 4 show that the variability of the transfer function of the drying chamber for all three exposure channels is significant.

The transfer function in the channel: temperature of the heat carrier - the temperature of the grain $\theta_{hc} \rightarrow \theta_c$ has the greatest variability, as evidenced by the values of the standard deviation and the variation coefficient. This is due to significant fluctuations in the initial moisture content and initial temperature for heat and mass transfer processes during the drying process. The transfer function in the channel: temperature of the heat carrier - moisture content of the grain $\theta_{hc} \rightarrow W_c$ has the least variability. This can be explained by a relatively thick bed of grain - 200 mm and by the experimental technique, when the volume-averaged moisture content was recorded, which was calculated from the loss of grain weight during the drying process.

4. Conclusions

The transfer functions of the drying chamber are obtained for drying grain in a convective way in a dense bed through three control channels: heat carrier temperature $\rightarrow$ grain moisture content, heat carrier temperature $\rightarrow$ grain temperature and heat carrier temperature $\rightarrow$ worked out heat carrier temperature at various dynamic properties of the drying: initial moisture content of grain, initial grain temperature and heat carrier temperature. The transfer functions depending on the exposure channel and the values of technological parameters either represent a first-order lag, or series-connected lead network and first- or second-order lag. Different types of transfer functions for one exposure channel do not allow obtaining a model describing the dependence of the parameters of transfer functions on the parameters of the technological process.

Evaluation of the frequency properties of transfer functions allows us to conclude that within the range of variation of the heat carrier temperature, initial temperature and initial moisture content of the grain, the drying chamber is an object with a significant phase and range stability margin.

The inertial characteristics of the drying chamber change significantly when the parameters of the technological process change. The maximum relative range of variations of the output rise time under a single exposure has the exposure channel: heat carrier temperature - the temperature of the worked out heat carrier, which is 2.84.

A significant variability of the dynamic properties of the drying chamber was revealed, which was estimated by the scattering of the PI controller setting when the object with the studied transfer functions was included in the automatic control system. According to the calculation results of relative variation range, standard deviation and variation coefficient the exposure channel: the heat carrier temperature - the grain temperature has the greatest variability.

References

[1] Andrianov N M 2004 The successes of modern natural science 9 86-91
[2] Andrianov N M Mei Shunchi and Xue Yu 2015 Fundamental research 2(16) 3459-65
[3] Lykov A V 1968 Drying theory (Moscow: Energiya) 472
[4] Pitsyn S D 1966 Grain dryers, technological bases, thermal calculation and structures (Moscow: Mashinostroenie) 211
[5] Tsuglenok N V and Manasyan S K 2008 KrasGAU Bulletin 6 139-45
[6] Manasyan S K 2004 KrasGAU Bulletin 4 151-56
[7] Andrianov N M, Galkin A D, Mei Shunchi, Xue Yun, Nikolaenok A V, Ivanov M A and Mikhailov A S 2015 Polzunovsky Almanoch 2 9-54
[8] Andrianov N M, Mei Shunchi, Chen Jen and Li Jen 2014 Basic research 11(2) 259-65
[9] Giner Sergio A 2019 Biosystems Engineering 186 228-33
[10] Giner Sergio A, Ricardo M and Torrez Irigoyen 2017 Biosystems Engineering 157 99-108
[11] Zakhakhatnov V G and Kashin P V 2018 VIESH Bulletin 1(30) 33-7