Synthesis of a Robust Controller for a Small Turbojet Engine

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Abstract: **-** The paper considers an automatic control system for a small gas turbine engine. The synthesis of a controller providing an increase in the speed of the control system was carried out using the standard procedures of the Matlab system. The transfer function of the control object is obtained with interval coefficients that take into account the possible effects of the uncertainties of the models under study. A graphical method of displaying the obtained results in the form of displaying the fuzzy branches of the root locus on the complex plane is used, which clearly shows the robust absolute stability of the system under study. The superiority of the proposed result over the existing ones is demonstrated by numerical examples. The simulation performed in the Matlab environment confirmed the correctness of the obtained results.

KeyWords: **-** stability, robust absolute stability, parametric uncertainty, interval polynomial

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1 Introduction

To solve complex aviation problems, it is necessary to develop new approaches to the study of dynamic engine models. Usually, when constructing such a dynamic model, approaches are used that are used to study complex nonlinear systems. In recent years, a large number of publications have been devoted to small gas turbine engines. These publications can be conditionally divided into several groups. The first group describes solutions related to improving the design of the engine, [1-5], the other group explores the models obtained to obtain the required characteristics of gas turbine engines, [6-8]. In addition to the above, there is a group of publications related to the study of engine control systems [9–19]. In [1], the influence of the choice of the operating point on the accuracy of the obtained model is estimated using identification methods based on experimental data. The article [2] describes the results of experimental and computational work in order to use alternative fuels in gas turbine engines. An experimental study on the injection of compressed air when starting a micro jet engine to improve its performance was carried out in [3]. The content of the publication [4] concerns the experimental and numerical study of combustion processes in a chamber used in ultra-small jet engines. The work [5] presents two sections – theoretical and experimental. The theoretical section describes the design of the electronic control unit based on the analysis of the engine start process. The experimental section presents the design of the electronic control unit. The article analyzes the features of the launch process of a small turbojet engine, and also puts forward the idea of building models in accordance with the various phases of the launch process. In [6], simulations were carried out to obtain the thermodynamic and performance characteristics of gas turbine engines. A device was also developed for the main technologies for increasing thrust. The content of the publication [7] concerns the development of a practical system for monitoring the condition of a small turbojet engine to check not only the condition of engine performance by comparing performance measurement data, but also the condition of the gas path components. In [8], a linear mathematical model of a small-sized turbojet engine with a controlled nozzle constriction was developed and studied. The development of an adaptive controller for a class of small turbojet engines with a threeloop control architecture is given in [9, 10]. In [11], the use of fuzzy norms T and S in the Min-Max selection strategy to improve the performance of the controller and the dynamic behavior of the gas turbine engine is considered. In [12], experimental identification methods are described applied to a system with two inputs and two outputs, as well as mathematical modeling of a small-sized iSTC-21v turbojet engine with a variable exhaust nozzle. Since the control systems of a gas turbine engine are complex systems with many uncertainties, fundamental methods of robust control can be applied to study these systems [13-16]. Robust control of turbojet engines has also attracted the attention of many researchers [17–21]. It was found that to ensure high quality of robust control of a small gas turbine engine, it is a control based on the norm H∞ [17,18].

2 Problem Formulation

In [19], an approach and a method for designing robust controllers are proposed, taking into account the limitations and features of a real small turbojet engine and its equipment, which can be used in a discrete digital control environment. In the article, an attempt was made to synthesize an interval-robust controller based on the use of the synthesis method proposed in [17]. For this, a mathematical model of the iSTC-21v small turbojet engine with an adjustable exhaust nozzle was chosen. Models were built for each of the six operating points, obtained using experimental identification methodology [1],[12]. The models were evaluated using standard scores, mean absolute error (MAE), and maximum absolute error (MAAE), as well as their percentages (MAAPE and MAPE). These models were used to determine the uncertainties. The models had high gain, so they were very sensitive to changes in control inputs and noise. The task is to carry out the synthesis of a controller that provides an increase in the speed of the control system, using the standard procedures of the Matlab system. In addition, we construct an interval root locus for the obtained interval transfer function, which confirms the robust absolute stability of the system under study.

3 Problem Solution

The nominal motor model was calculated as the average value of the coefficients of a separate model, while the resulting transfer function was determined as follows [19]

$$W_{nom}(s) = \frac{4879s+1.468e04}{s^2+2.805s+2.325}. \quad (1)$$

On the basis of the obtained model, we will construct a block diagram of a digital-analogue control system, shown in Fig.1.

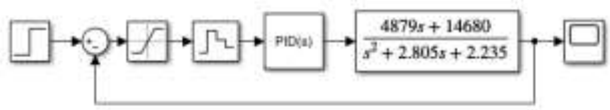

Fig.1. Structural diagram of a digital-analog control system

3.1. Synthesis of a discrete controller

Let's perform the synthesis of a discrete proportional integral-derivative (PID) controller of the turbojet engine control system in the MatLab environment. To do this, we subject the transfer function of the control object (1) to a discrete z-transform, taking into account the presence of a zero-order extrapolator in it for the accepted discrete period T=0.01c, as a result, we obtain a discrete transfer function of the control object of the following form

$$W_{nom}(z) = \frac{48{,}84z-47{,}39}{z^2-1{,}972z+0{,}9723}. \quad (2)$$

Various methods can be used to synthesize a discrete speed controller for a small turbojet engine: providing modular or symmetrical optima, polynomial equations, minimum integral estimates, etc. To solve complex problems associated with the elimination of uncertainties in the control of turbojet engines, the robust control methodology described in the fundamental literature, [13], [14], [15], [16], can be applied. The presented results show that this methodology can provide high quality control in a wide range of operating states of complex systems. Therefore, it can be considered a suitable candidate for use in the efficient control of turbojet engines. Based on current research in the field of reliable control of turbojets, the method mainly used in the control of turbojets in current publications is control based on the H∞ norm, [18],[20].

However, many of them give the transfer function of the controller of a sufficiently high order and poorly realize the possibilities of achieving system speed. In this regard, for the synthesis of the controller, it is advisable to use the standard PID controller and the Matlab software package, which has tools for automatic tuning of PID controllers. In connection with the foregoing, the synthesis of a digital controller is feasible using the pidtune program, which allows you to set the desired phase shift of an open-loop system and, by changing the gain of the proportional channel, achieve the desired nature of transients and their speed. At the same time, it should be borne in mind that the larger the phase margin, the greater the level of robustness of the system being designed. As a result of calculations, the following discrete transfer function of the PIDF controller was obtained

$$Wp(z) = \frac{0{,}002128z - 0{,}002106}{z-1}. \quad (3)$$

The differential component of the controller is excluded from the transfer function due to the very low transmission coefficient for this channel, as shown in [13]. The synthesized regulator provides a margin of 82 degrees. and transient time 0.67 s. In order to achieve sufficient speed, the transient function is assumed to be oscillatory with an overshoot of 6%, which is shown in Fig.2.

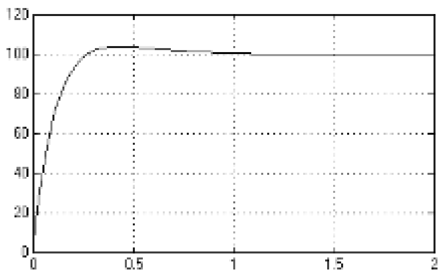

Fig. 2. Transition function at nominal parameters of control system

In this case, the transfer function of an open-loop system can be written in the form

$$W_{rnom}(z) = \frac{0{,}1039z^2 - 0{,}2037z + 0.09982}{z^3 - 2.972z^2 + 2{,}944z - 0{,}9723}. \quad (4)$$

For a preliminary assessment of the degree of robustness of the synthesized control system, we will use its approximate dependence on Mr- the maximum value of the frequency response of a closed discrete control system. Let's build the frequency response of a closed discrete system in Fig.3.

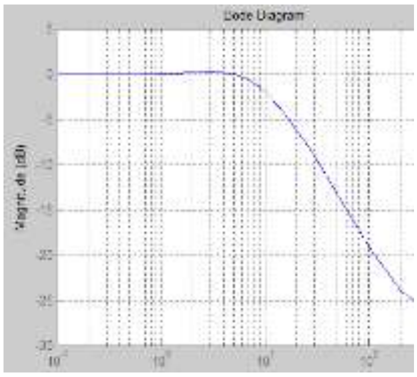

Fig.3. Frequency response of a closed discrete control system

The maximum value of the PFC is 0.218 dB at a frequency of 3.47 rad/s, which corresponds to a fairly high degree of robustness.

3.2. Obtaining transfer functions of the studied models

Let us carry out similar calculations with the resulting controller for transfer functions with maximum and minimum coefficients, which will be written respectively in the form [19]

$$W_{max} = \frac{8219s + 13380}{s^2 + 3.298s + 1.936}. \quad (5)$$

$$W_{min} = \frac{1154s + 2758}{s^2 + 2.31s + 0.5891}. \quad (6)$$

From (5,6), taking into account (3), we obtain for objects with maximum and minimum coefficients discrete transfer functions of open-loop systems of the following form

$$W_{rmax}(z) = \frac{0{,}1734z^2 - 0{,}3423z + 0.1689}{z^3 - 2.967z^2 + 2{,}935z - 0{,}9676}. \quad (7)$$

$$W_{rmin}(z) = \frac{0{,}02456z^2 - 0{,}0483z + 0.02374}{z^3 - 2.977z^2 + 2{,}954z - 0{,}9722}. \quad (8)$$

In this case, the transition functions of the models under study are shown in Fig.4.

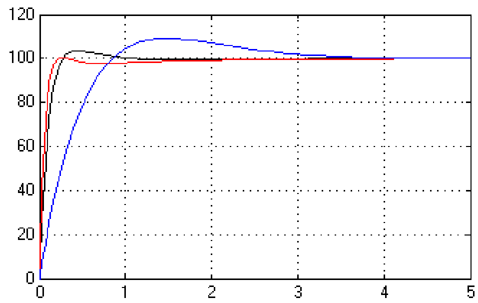

Fig.4. Transient functions of systems with minimum, nominal and maximum sets of model parameters

3.3. Investigation of the absolute stability of the considered models

Let us study the stability of the considered models by constructing a root locus. To do this, we obtain the transfer functions (4,7,8) in the w-form. As a result, we obtain the transfer functions of the systems under study with maximum, nominal and minimum coefficients, which have the following form

$$W_{rmax}(w) = \frac{-0.087w^3+17{,}17w^2+45{,}65w+28.43}{w^3+3.298w^2+1{,}936w+8{,}046E^{-10}}. \quad (9)$$

$$W_{rnom}(w) = \frac{-0.05165w^3+10{,}12w^2+41{,}29w+31.19}{w^3+2.805w^2+2{,}325w-1{,}375E^{-10}}. \quad (10)$$

$$W_{rmin}(w) = \frac{-0.01222w^3+2{,}402w^2+8{,}261w+5.861}{w^3+2.31w^2+0{,}5891w-5{,}742E^{-10}}. \quad (11)$$

Root locus for models (9-11) are presented respectively in Figs. 5-7.

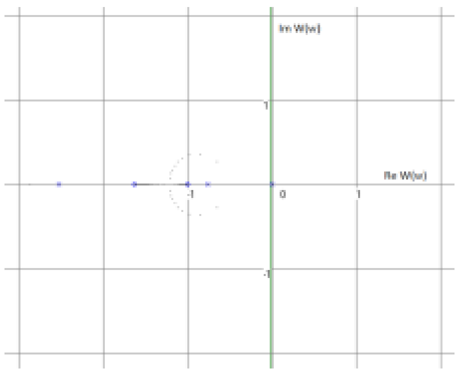

Fig. 5. Root locus for a system with maximum coefficients

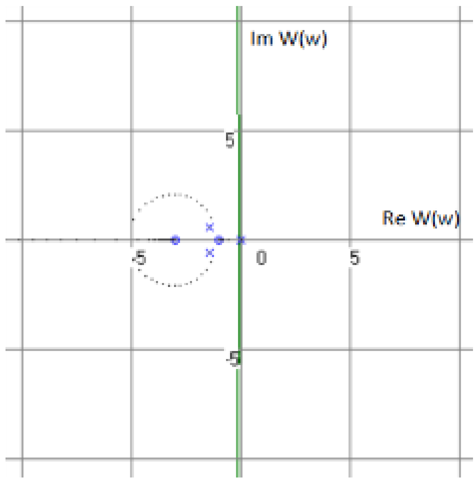

Fig. 6. Root locus for a system with nominal coefficients

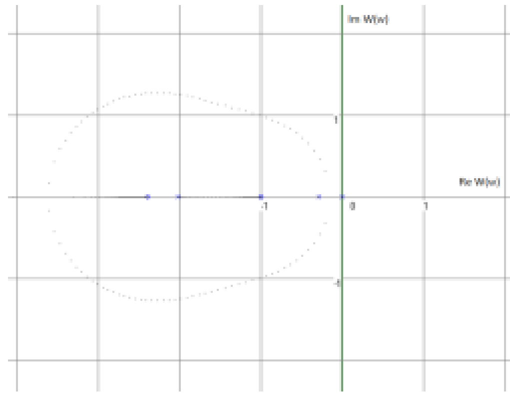

Fig. 7. Root locus for a system with minimum coefficients

3.4. Study of Robust Absolute Stability of Models

To study the robust absolute stability of models, we use a graphical approach [21] based on constructing a root locus for an interval transfer function whose numerator and denominator coefficients are obtained from transfer functions (5,7).

The transfer function with interval coefficients is written as

$$W_r(w) = \frac{\begin{matrix}-(0{,}087..0{,}01222)w^3+(2{,}402..17{,}17)w^2+\\ +(8{,}261..45{,}65)w+(5{,}861..28.43)\end{matrix}}{\begin{matrix}(1{,}0..1{,}0)w^3+(2{,}31..3{,}298)w^2+\\ +(0{,}5891..1{,}936)w+(-5{,}742E^{-10}..8{,}046E^{-10})\end{matrix}}. \quad (12)$$

The resulting interval root locus is shown in Fig. 8.

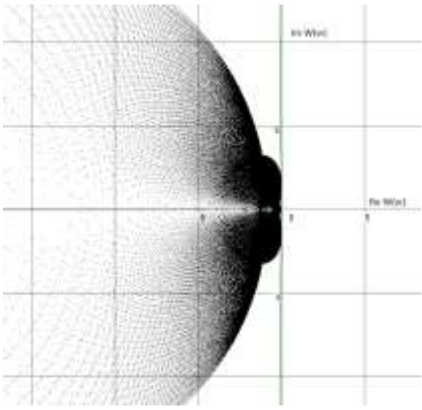

Fig. 8. Root locus of the studied models with interval coefficients

It can be seen from the figure that all the blurred trajectories of the branches of the interval root locus do not fall on the real positive axis, which indicates the robust absolute stability of the discrete models under study.

4 Conclusion

The proposed approach to the study of discrete models of small gas turbine engines has shown that it is possible to use a PID controller, which is easier to implement in practical conditions and, in addition, provides robust absolute stability of these models.

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

Author Contributions: Please, indicate the role and the contribution of each author:
Tseligorov N.A. conducted a study of the control system of a small gas turbine engine for robust stability.
Chubukin A.V. investigated this control system taking into account the synthesized PID controller.
Zhukov A.V. did the simulation.