UDC 533.697.3
doi: 10.32620/aktt.2021.1.03

A. KULIK, S. PASICHNIK, D. SOKOL

National Aerospace University «Kharkiv Aviation Institute», Ukraine

MODELING OF PHYSICAL PROCESSES OF ENERGY CONVERSION IN SMALL-SIZED VORTEX ENERGY SEPARATORS

The object of study in the article is the vortex effect of temperature separation in a rotating gas flow, which is realized in small-sized vortex energy separators. The subject matter is the models that describe the physical processes of energy conversion in small-sized vortex energy separators as objects of automatic control. The goal is to obtain models of a vortex energy separator reflecting its static and dynamic properties as an automatic control object. The tasks to be solved are: to develop a three-dimensional computer model of a small-sized vortex energy separator which will allow analyzing the parameters of the gas flow and physical processes of energy conversion directly inside the object and obtaining its static characteristics. A linearization method of static characteristics on the interval of input and output values is proposed which will expand the operating range without loss of linearization accuracy. A method of structural-parametric identification based on experimental logarithmic magnitude-frequency characteristics is proposed which will allow for the same set of experimental points to select the structure of the mathematical model of varying complexity depending on the specified accuracy. As a result of the work, the scheme for modeling the automatic control object was formed, consisting of the drive unit, sensor unit, and vortex energy separator, with the reflection of all the obtained operating modes. The methods used are the method of graphic linearization, Laplace transform, structural-parametric identification. The following results were obtained: a computer and linearized mathematical model of the small-sized vortex energy separator as an automatic control object reflecting its properties in the time and frequency domains was obtained. A comparative analysis of the reactions of the model and the real object to the same input action was carried out. Conclusions. The scientific novelty of the results obtained is as follows: 1) multiple graphic linearizations of one static characteristic to use the full range of the operation mode of vortex energy separator, which distinguishes it from the known;2) mathematical model structural-parametric identification for vortex energy separator with the help of known points of the Bode magnitude plots by using the interpolation polynomial and its derivatives graphs.

Keywords: *vortex effect; vortex energy separator; computer model; graphic linearization; frequency characteristics; identification; automatic control object; simulation scheme; transfer function.*

Introduction

A vortex energy separator is a device in which the vortex Ranque effect is realized [1]. In the modern world, vortex energy separators are used for gas purification, in the automotive industry, in industry as part of refrigeration systems and cooling systems [2]. In this article, the vortex energy separator is considered as a nonlinear control object that does not have a standard equation describing its dynamic properties.

One of the main tasks solved in the design of automatic control systems is the identification of the control object, which consists in obtaining its mathematical description. The nature and type of mathematical model is determined by the goals and objectives for which it will be used. In this work, the identification problem is to determine the structure and parameters of the mathematical model of a nonlinear control object with unknown dynamics from the obtained experimental data.

The control object is characterized by certain properties. The relationship between the input and output signals of an object, the change in state over time are often described by analytical expressions, which become standard as a result of repeated theoretical studies and experimental confirmation. Nevertheless, there are such objects for which mathematical models in analytical form have not been obtained, or depend on the area of knowledge in which such objects are used. The presence of an analytical description of dynamic properties allows a wider range of identification methods, simplification of the mathematical model, or transitions to other necessary forms of presentation to be applied. In other cases, it becomes necessary to carry out a series of experiments to obtain various types of characteristics, and, based only on these data, to solve the problem of identifying a single research object.

Automatic control theory includes methods for identifying and assessing the process state. The choice of the identification method depends on the properties of control object. In practice, solving the identification issue with accuracy is a complex procedure, its implementation is carried out using expert solutions.

The purpose of the paper is to describe the proposed methods of structural and parametric identification of the mathematical model of the vortex energy separator and the use of the results obtained to implement the model of a rational control system [3]. The article uses data from the experimental setup based on vortex energy separator that has a specific design and fixed dimensions. So the results obtained will be valid for vortex energy separators of that type.

1. The arrangement and operation principle of the vortex energy separator

The experiments on the mock-up model [4] which has the following geometric characteristics: diameter of working part $D_{wp} = 5{,}8\,\text{mm}$, length of working part $L_{wp} = 116\,\text{mm}$, stroke of valve regulator $\Delta\zeta = 2\,\text{mm}$, diameter of diaphragm $D_d = 2{,}5\,\text{mm}$, area of the tangential inlet $F_n = 1\,\text{mm}^2$. Environment factors: compressed air pressure $P = 0{,}5...0{,}7$ MPa, temperature of environment $T_{env} = 292\,\text{K}$. The series of experiments conducted by associate professor S. N. Pasichnik at the department of Aircraft Control Systems of the National Aerospace University «Kharkiv Aviation Institute». The appearance of mock-up model is shown in Fig. 1.

As a result of experiment, a number of static, logarithmic magnitude-frequency and transient characteristics have been obtained.

The information scheme reflecting the movement of the air flow inside the components of the vortex energy separator is shown in Fig. 2.

In fig. 3 shows the result of CFD simulation for the three-dimensional model of vortex energy separator according to the geometric characteristics of the experimental setup. The computer model includes solid structural elements, air parameters, air flow control unit (adjusting valve). The parameters of the air determine the steady-state operation mode of the vortex energy separator. Temperature, pressure and air mass flow have been considered as the target flow parameters. Temperature is the main parameter that has been chosen for quantitative assessment of the effective and adequate operation of the model [5].

As a result of the choice of the adjusting valve position the transmission coefficients for the vortex energy separator are determined

$$k_{OC} = \Delta T_{OC} / \Delta\xi, \tag{1}$$

$$k_{OH} = \Delta T_{OH} / \Delta\xi, \tag{2}$$

where ξ – adjusting valve position, mm, T_{OC}, T_{OH} – cold and hot air outlet temperature, ^{O}C.

The adequate computer model of vortex energy separator allows to measure and evaluate parameters at any point of the model that cannot be determined in real conditions due to shortcomings of measuring devices or due to design features.

Fig. 1. Appearance of experimental mock-up model based on the small-sized vortex energy separator

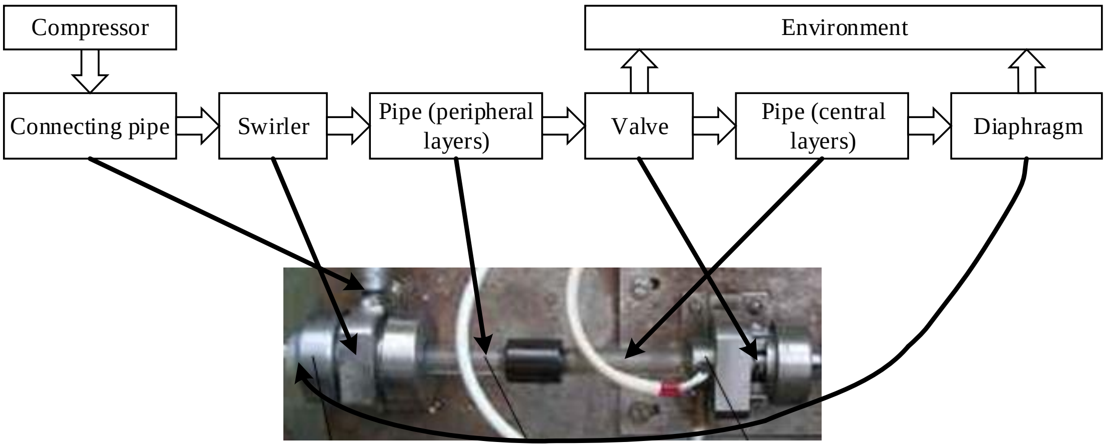


Fig. 2. Information scheme of air flow movement inside the components of the vortex energy separator

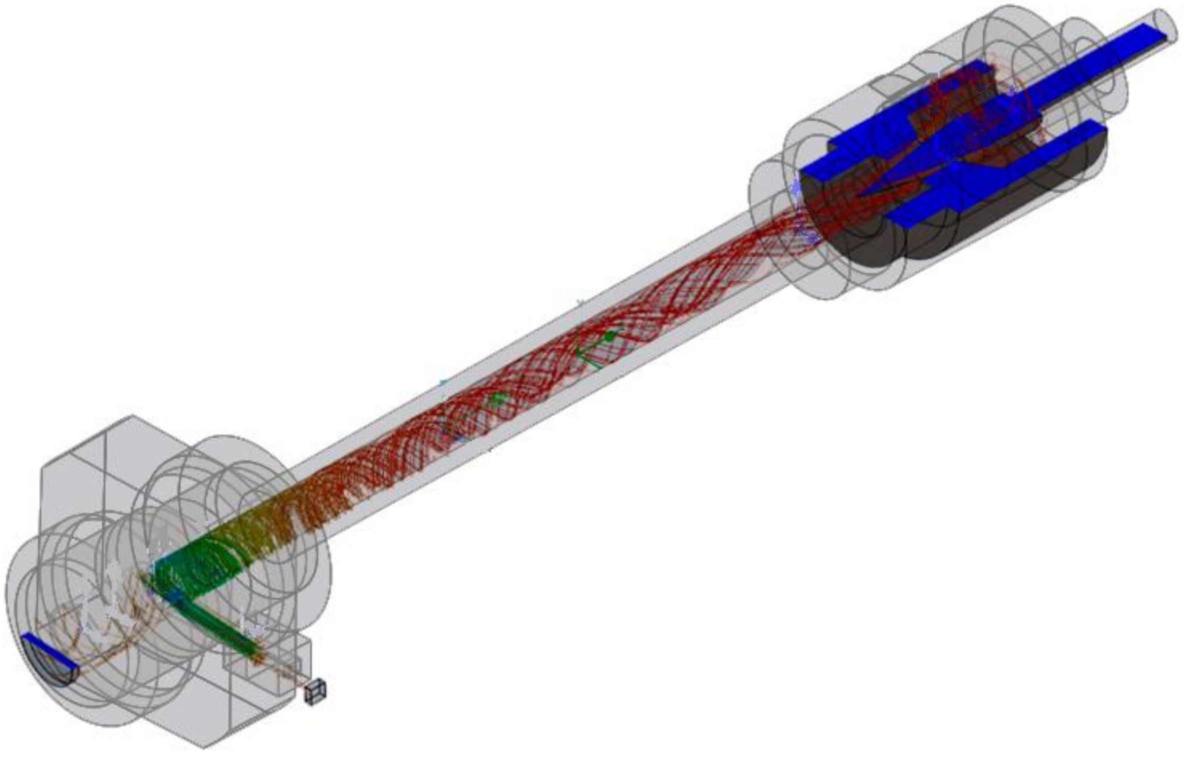


Fig. 3. Computer model of the vortex energy separator

The disadvantage of computer model is the using idealized model of the real plant. When the model is being developed some parameters can be incorrect or may not be mentioned, so using such calculations will affect the operation and accuracy of the designed object.

2. Linearization of static characteristics

As a result of experiments with the computer model the static characteristics of the vortex energy separator have been obtained as the dependence of the temperatures of cold and hot air flows on the valve position when inlet air pressure is 0.5, 0.6, or 0.7 Pa.

For objects that have a nonlinearity similar to the vortex energy separator it is proposed to carry out linearization over the entire signal range with a lower error than with point linearization over the same range. In fig. 4 shows the values of cold air flow temperature when adjusting valve moves along its entire possible diapason for each value of inlet air flow pressure.

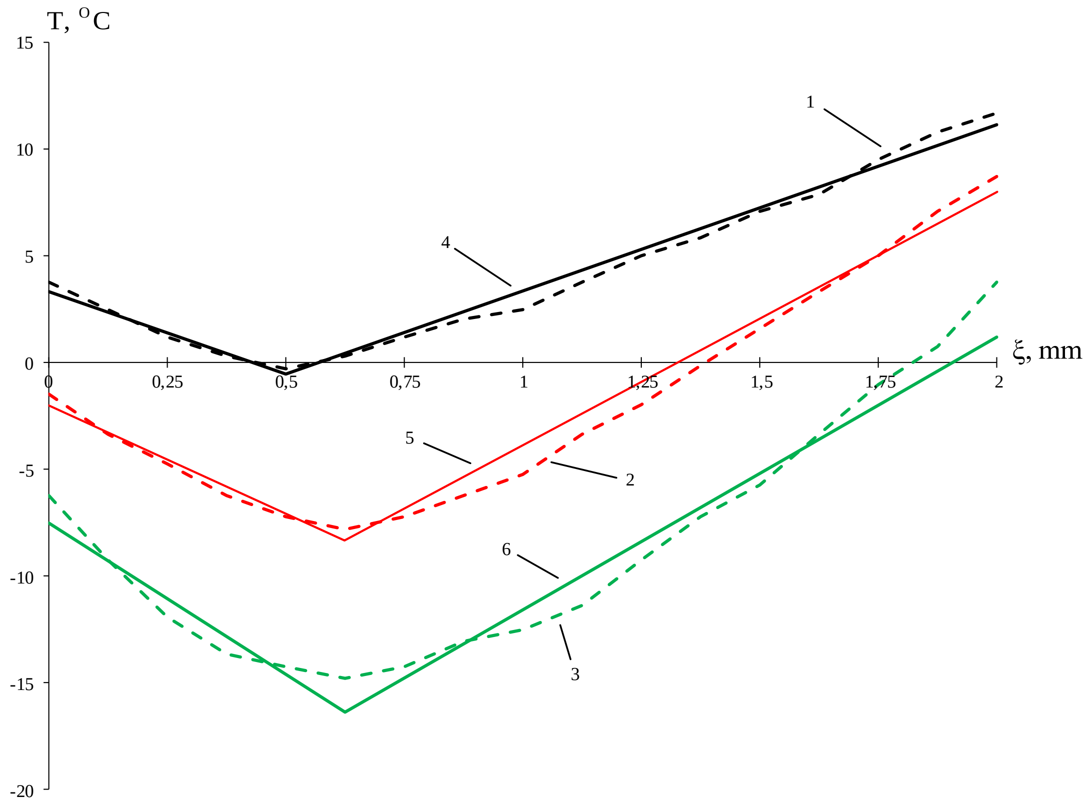


Fig. 4. Dependence of the cold air flow temperature on the adjusting valve position for different values of pressure and corresponding linearized characteristics: 1 – experimental characteristic when 0.5 MPa; 2 – experimental characteristic when 0.6 MPa; 3 – experimental characteristic when 0.7 MPa; 4 – linearized characteristic when 0.5 MPa; 5 – linearized characteristic when 0.6 MPa; 6 – linearized characteristic when 0.7 MPa

In a similar way the interval linearization of static characteristics has been carried out as the dependence of the hot air flow temperature on the adjusting valve position.

In such way, several operating points are determined, twelve operation modes of the vortex energy separator have been formed:

- pressure 0.5 MPa, valve position less than 0.5 mm by the cold air flow;
- pressure 0.5 MPa, valve position more than 0.5 mm by the cold air flow;
- pressure 0.5 MPa, valve position less than 0.875 mm by the hot air flow;
- pressure 0.5 MPa, valve position more than 0.875 mm by the hot air flow;
- pressure 0.6 MPa, valve position less than 0.625 mm by the cold air flow;
- pressure 0.6 MPa, valve position more than 0.625 mm by the cold air flow;
- pressure 0.6 MPa, valve position less than 0.875 mm by the hot air flow;
- pressure 0.6 MPa, valve position more than 0.875 mm by the hot air flow;
- pressure 0.7 MPa, valve position less than 0.625 mm by the cold air flow;
- pressure 0.7 MPa, valve position more than 0.625 mm by the cold air flow;
- pressure 0.7 MPa, valve position less than 0.875 mm by the hot air flow;
- pressure 0.7 MPa, valve position more than 0.875 mm by the hot air flow.

The numerical values of the transmission coefficients according to (1) and (2) for each mode of operation will be presented in Section 4.

3. Model identification based on Bode magnitude plot

An alternative method for determining the mathematical model of object is proposed based on obtaining a number of experimental logarithmic frequency characteristics and graphical identification. The graphical identification presented in this work is associated with the Bode magnitude plot.

The Bode magnitude plot of the vortex energy separator obtained as a result of number of experiments has been taken as the initial data [6]. The accuracy of determining the model structure depends on the requirements for the accuracy of its obtaining. The use of Bode magnitude plot assumes the determination of the break frequencies. They can be clearly displayed on the asymptotic characteristic, however, they are implicitly expressed on the experimental plot.

The following approach is proposed for finding the break frequencies. The original graph is interpolated by a polynomial of (n-1) order where n is the number of experimental points on the graph. The experimental logarithmic characteristic has eight points, therefore, it is definitely possible to obtain the 7th order polynomial shown in fig. 5.

$$y = p_7x^7 + p_6x^6 + p_5x^5 + p_4x^4 + p_3x^3 + p_2x^2 + p_1x + p_0, \quad (3)$$

where $p_7 = 37.149$; $p_6 = 234.77$; $p_5 = 570.87$; $p_4 = 654.74$; $p_3 = 331.14$; $p_2 = 25.016$; $p_1 = -40.441$; $p_0 = -18.802$.

The derivatives of the polynomial (3) are used to find the break frequencies [7]. For the 7th order polynomial the following is defined: the graph of the 1st derivative can be used to identify the model with the highest accuracy (when using this approach), the graph of the 3rd derivative - with less accuracy, the graph of the 5th derivative - with the least (for given polynomial) accuracy.

1st derivative of a polynomial is a 6th order polynomial

$$y = p_6x^6 + p_5x^5 + p_4x^4 + p_3x^3 + p_2x^2 + p_1x + p_0, \quad (4)$$

where $p_6 = 260.043$; $p_5 = 1408.62$; $p_4 = 2854.35$; $p_3 = 2618.96$; $p_2 = 993.42$; $p_1 = 50.032$; $p_0 = 40.441$.

3rd derivative of a polynomial is a 4th order polynomial

$$y = p_4x^4 + p_3x^3 + p_2x^2 + p_1x + p_0, \quad (5)$$

where $p_4 = 7801.29$; $p_3 = 28172.4$; $p_2 = 34252.2$; $p_1 = 15713.76$; $p_0 = 1986.84$.

5th derivative of a polynomial is a 2nd order polynomial

$$y = p_2x^2 + p_1x + p_0, \quad (6)$$

where $p_2 = 93615.48$; $p_1 = 169034.4$; $p_0 = 68504.4$.

The break frequencies are calculated from the given graphs by the local extrema of the graphs of the derivatives of the initial polynomial. If the plot has a local minimum, the value of which takes a negative value, then it defines a pole of the desired model. If the plot has a local maximum, the value of which takes a positive value, then at this point there is a zero of the desired model. The rest of the local extrema do not determine the presence of the break frequency.

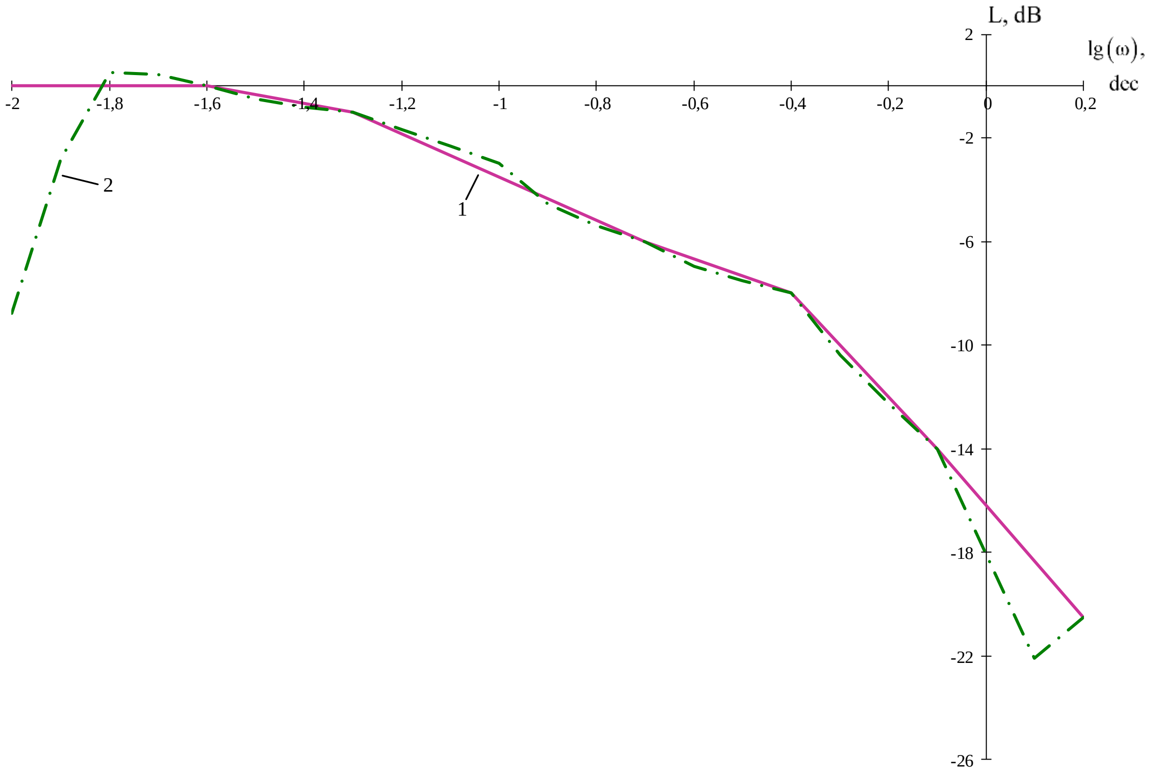


Fig. 5. Experimental logarithmic frequency response and 7th order polynomial plot:
1 – experimental characteristic; 2 – 7th order polynomial plot

Based on this, three local minima with negative values and two local maxima with negative values are clearly expressed on the graph of the 6th order polynomial (4). These minima indicate the presence of three poles but maxima do not indicate the presence of zeros. The 4th order polynomial (5) indicates two local minima with negative values and one local maximum with a positive value. These minima indicate the presence of two poles, the positive maximum indicates the presence of zero. The 2nd order polynomial (6) indicates only one local minimum with a negative value that indicates the presence of pole. Aperiodic and forcing links of the 1st order for each corresponding break frequency are selected. So the transfer functions defined by three derivatives will have the form like

$$W(s) = Y(s)/X(s) = 1/((T_1s+1)(T_2s+1)(T_3s+1)) = \\ =1/((43.85s+1)(8.2s+1)(1.1s+1)); \qquad (7)$$

$$W(s) = Y(s)/X(s) = (T_2s+1)/((T_1s+1)(T_3s+1)) = \\ = (10s+1)/((25.12s+1)(2.5s+1)); \qquad (8)$$

$$W(s) = Y(s)/X(s) = 1/(Ts+1) = 1/(6.3s+1). \qquad (9)$$

The Bode magnitude plots are shown in fig. 6.

The estimated Bode magnitude plot are not an approximation of the experimental Bode magnitude plot. For better approximation, two options are proposed: shift the estimated Bode magnitude plot by using the additional transmission coefficient or conduct more thorough analysis of the graphs of the derivatives of the polynomial.

It is assumed that the value of the local extremum that determines the presence of the break frequency affects the slope of the asymptotic Bode magnitude plot: when the value increases the slope increases for absolute values.

Using this approach, the time constants of the aperiodic function have been obtained as the mathematical description of the vortex energy separator T = 9.7, T = 8, and T = 5.6 when inlet air pressures of 0.5, 0.6, and 0.7 MPa, respectively.

4. Block diagram of the automatic control object

In fig. 7 shows the model of vortex energy separator as an automatic control object [3] created in Simulink.

Bias 1.57 and 4.57 are the nominal voltage values of the sensors, corresponding to -1.9 and 44 as the temperatures of the hot and cold air flows at the valve zero position.

The actuator unit consists of the actuator transfer function, that is physically a combination of a stepper motor and a variable displacement valve. For each model, non-linearity is applied in the form of saturation, that is physically caused by the limited range of valve movement in millimeters.

The value of the air flow pressure supplied to the working area of the vortex energy separator affects the parameters of the air flows leaving it. At the scheme, the choice of the pressure value is carried out among the set of values (0.5, 0.6 or 0.7 MPa), for which the mathematical models of the vortex energy separator have been experimentally obtained, and other different values of pressure (e.g. 0.8 MPa), that will be perceived by the system as uncertain or undesirable.

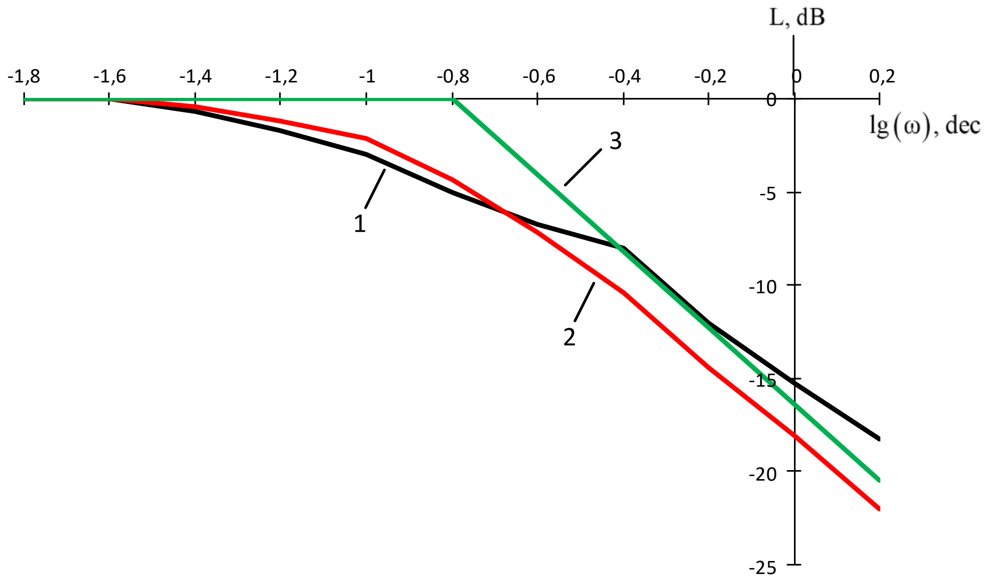


Fig. 6. The Bode magnitude plots by transfer function (9):
1 – experimental plot; 2 – estimated plot; 3 – estimated asymptotic plot

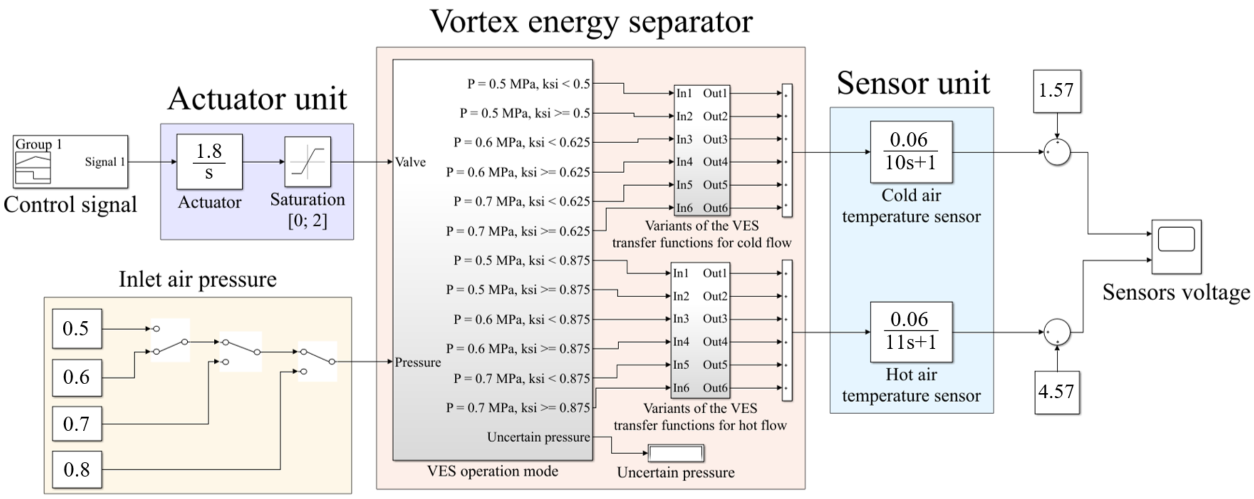


Fig. 7. Block diagram of the automatic control object

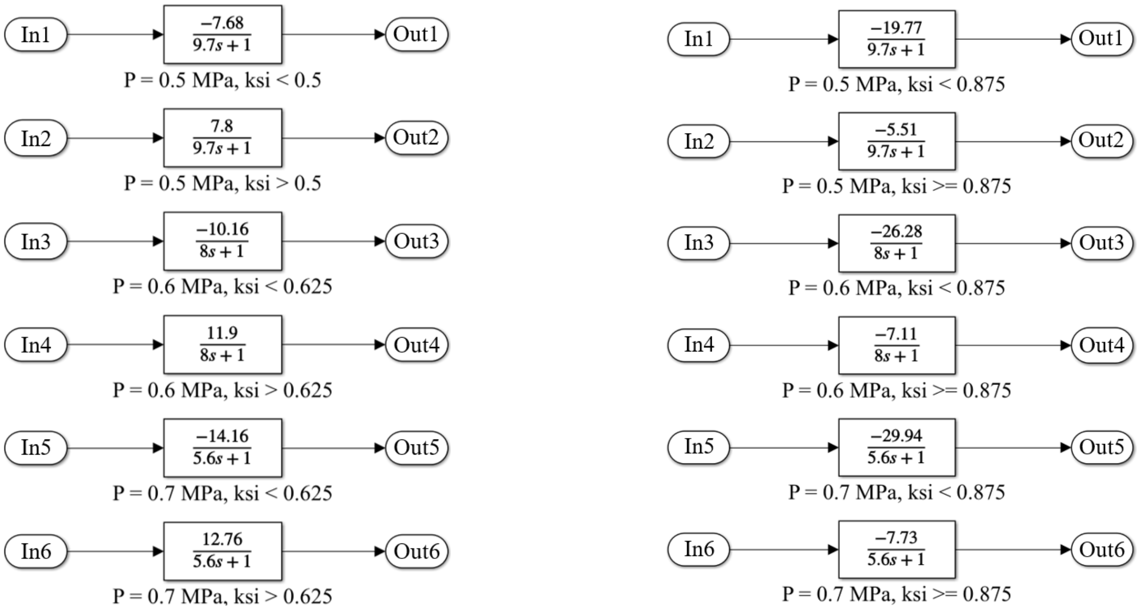
In the "Vortex energy separator" subsystem, the mathematical model of vortex energy separator is implemented in several parameters, taking into account the value of the inlet air pressure and the adjusting valve position. According to the selected operating mode, a pair of transfer functions of the vortex energy separator is determined: according to the cold and hot air flows.

All variants of the vortex energy separator operating mode have been used due to the subsystem "VES operation mode". The presented approach is carried out in two stages: the set air pressure is manually set, then the condition is imposed on the current valve position as a control signal.

The air pressure switching subsystem determines the value with which the system will operate. It is assumed that the supply air pressure is constant for one simulation iteration. The valve position operating mode, in turn, is determined continuously during the simulation time. The values of these positions are determined from the data of static characteristics of the vortex energy separator.

The sensor unit consists of two sensors that measure the temperature of cold and hot air flows. The operation range of each sensor exceeds the possible temperature range.

The model at a specific moment in time determines one of six transfer functions of the vortex energy separator for the cold flow and one of six for the hot flow, the structure and parameters of which have been obtained previously in Sections 2 and 3. The transfer functions are shown in Fig. 8.



a) b)

Fig. 8. Subsystems «Variants of the VES transfer functions for cold flow» (a) and «Variants of the VES transfer functions for hot flow» (b)

A pulse of unit magnitude and duration is set as an input signal for the system. The pulse size is chosen in such a way as to reach the actuator saturation zone and to activate several modes of vortex energy separator operation within one simulation.

The reaction of the vortex energy separator to the linear movement of the valve is a change in the values of the temperatures of cold and hot air flows, relative to their initial values according to the static characteristics of the vortex energy separator. The reaction of the automatic control object in the form of two transient processes are changes in the voltage of the temperature sensors and are shown in fig. 9.

In order to assess the performance of model of automatic control object a comparison has been made with the results of experiments that is shown in fig. 10, 11. Therein the input control signal is supplied with magnitude of 0.2 V and duration of 0.5 sec.

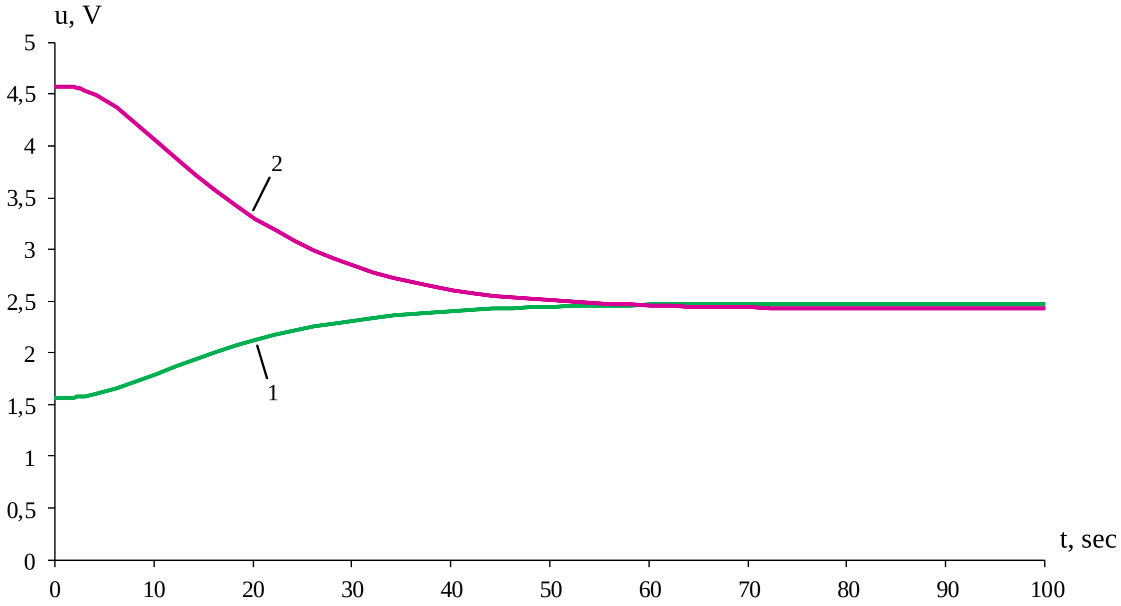


Fig. 9. Graphs of cold and hot air temperature sensors voltages:
1 – cold air temperature sensor voltage; 2 – hot air temperature sensor voltage

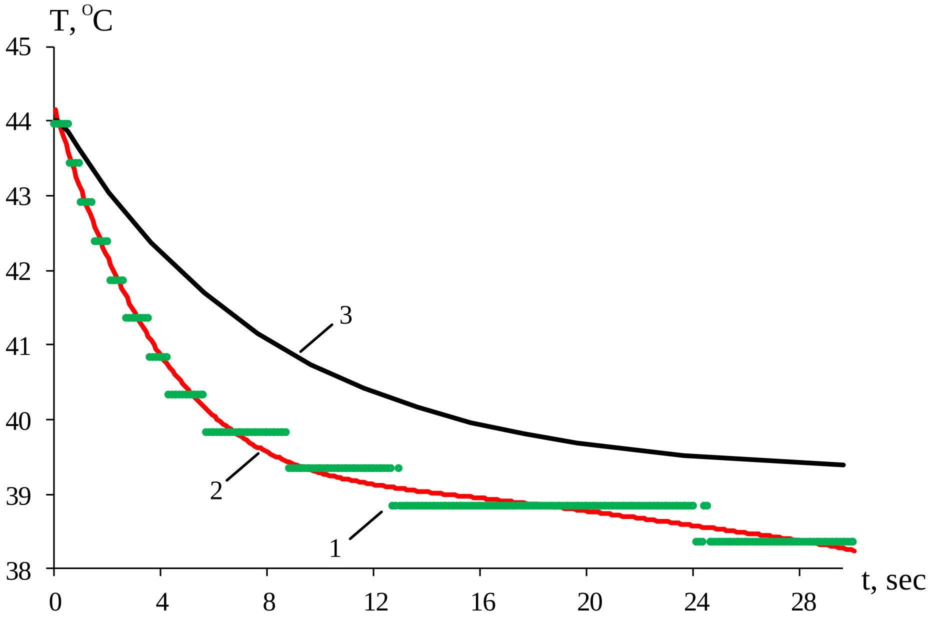


Fig. 10. Hot air flow temperature changing:
1 – experimental data; 2 – approximation of experimental data; 3 – model data

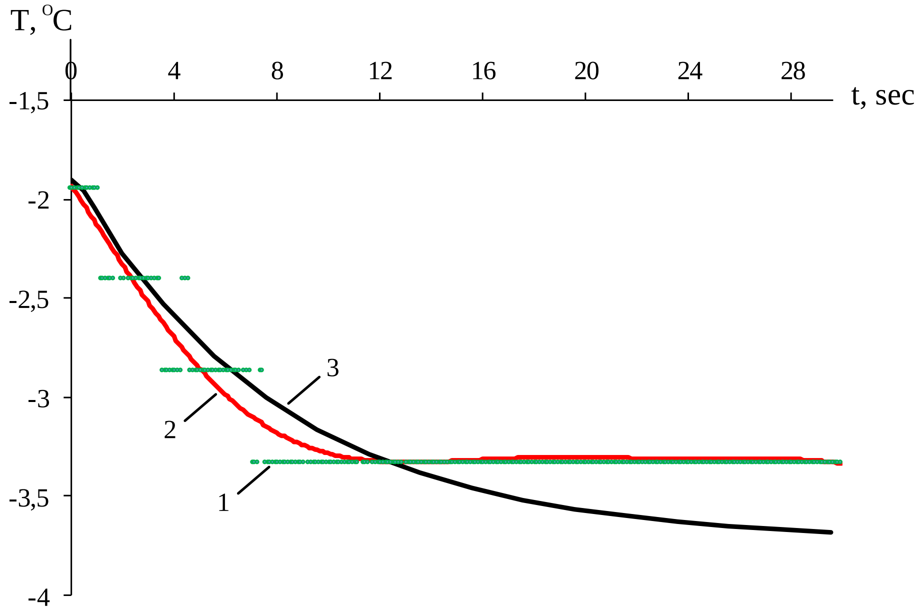


Fig. 11. Cold air flow temperature changing:
1 – experimental data; 2 – approximation of experimental data; 3 – model data

The maximum error of the hot air flow temperatures between the experimental data and model data is 1.5 °C, for cold air flow temperature is 0.4 °C.

Conclusions

The results of the work prove that the mathematical model of vortex energy separator obtained using interval linearization and the proposed approach to the analysis of Bode magnitude plots corresponds to the physics of the process occurring inside the object. The maximum error is 1.5 °C.

Further research will be aimed at describing the automatic control object in other forms of representation: in the state space, finite-difference equations, discrete transfer functions. The proposed frequency response analysis will also be refined. One of the main subsequent stages is the formation of block diagram of the automatic control object that makes it possible to recreate the destabilizing effects of circuit elements of various classes and types in order to analyze the efficiency of the vortex energy separator.

References (GOST 7.1 2006)

1. Анализ теплофизических процессов в вихревых трубах [Текст] / Ш. А. Пиралишвили, С. В. Веретенников, Г. Ш. Пиралишвили, О. В. Василюк // Вестник ПНИПУ. Аэрокосмическая техника. – 2017. – № 49. – С. 127–141.

2. Кулик, А. С. Применение эффекта Ранка-Хилша для управления вихревыми энергоразделителями [Текст] / А. С. Кулик, Д. В. Сокол // Авиационно-космическая техника и технология. – 2019. – № 3. – С. 15-27. DOI: 10.32620/aktt.2019.3.02.

3. Кулик, А. С. Элементы теории рационального управления объектами [Текст] : монография / А. С. Кулик. – Х. : Нац. аэрокосм. ун-т им. Н. Е. Жуковского «ХАИ», 2016. – 255 с.

4. Кулік, А. С. Апаратно-програмний комплекс для дослідження вихрового ефекту [Текст] / А. С. Кулік, В. Г. Джулгаков, С. М. Пасічник // Вісник ХНТУСГ. – 2010. – Вып. 102. – С. 85-87.

5. Hydraulic Flow Instability in a Ranque Tube. Journal of Applied Mechanics and Technical Physics [Text] / M. Kh. Pravdina, I. K. Kabardin, V. I. Polyakova, D. V. Kulikov, V. G. Meledin, V. A. Pavlov, M. R. Gordienko, N. I. Yavorsky // Journal of Applied Mechanics and Technical Physics. – 2020. – Vol. 3, no. 61. – P. 384–390. DOI: 10.1134/s0021894420030098.

6. Кулик, А. С. Идентификация математической модели вихревого энергоразделителя [Текст] / А. С. Кулик, С. Н. Пасичник // Авиационно-космическая техника и технология. – 2010. – № 10. – С. 192-196.

7. Кулик, А. С. Идентификация математической модели вихревого энергоразделителя в частотной области [Текст] / А. С. Кулик, С. Н. Пасичник // Авиационно-космическая техника и технология. – 2012. – № 7. – С. 192-196.

References (BSI)

1. Piralishvili, Sh. A., Veretennikov, S. V., Piralishvili, G. Sh., Vasilyuk, O. V. Analiz teplofizicheskikh protsessov v vikhrevykh trubakh

[Analysis of the thermophysical processes in the vortex tubes]. *Vestnik PNIPU. Aerokosmicheskaya tekhnika – Messenger PNIPU. Aerospace engineering*, 2017, no. 49, pp. 127-141.

2. Kulik, A. S., Sokol, D. V. Primenenie effekta Ranka-Khilsha dlya upravleniya vikhrevymi energorazdelitelyami [Application of the Ranque-Hilsch effect in control systems]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2019, no. 3, pp. 15-27. DOI: 10.32620/aktt.2019.3.02.

3. Kulik, A. S. *Elementy teorii ratsional'nogo upravleniya ob"ektami* [Elements of the rational control theory of objects]. Kharkiv, National Aerospace University “Kharkiv Aviation Institute” Publ., 2016. 255 p.

4. Kulik, A. S., Dzhulgakov, V. G., Pasichnik, S. N. Aparatno-prohramnyy kompleks dlya doslidzhennya vykhrovoho efektu [Hardware and software complex for investigating the vortex effect]. *Visnyk KhNTUSH – Messenger KhNTUSH*, 2010, no. 102, pp. 85-87.

5. Pravdina, M. Kh., Kabardin, I. K., Polyakova, V. I., Kulikov, D. V., Meledin, V. G., Pavlov, V. A., Gordienko, M. R., Yavorsky, N. I. Hydraulic Flow Instability in a Ranque Tube. *Journal of Applied Mechanics and Technical Physics*, 2020, vol. 3, no. 61, pp. 384–390. DOI: 10.1134/s0021894420030098.

6. Kulik, A. S., Pasichnik, S. N. Identifikatsiya matematicheskoi modeli vikhrevogo energorazdelitelya [Identification of the mathematical model of the vortex energy separator]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2010, no. 10, pp. 192-196.

7. Kulik, A. S., Pasichnik, S. N. Identifikatsiya matematicheskoi modeli vikhrevogo energorazdelitelya v chastotnoi oblasti [Identification of the mathematical model of the vortex energy separator in the frequency domain]. *Aviacijno-kosmicna tehnika i tehnologia – Aerospace technic and technology*, 2012, no. 7, pp. 192-196.

Надійшла до редакції 14.12.2020, розглянута на редколегії 16.02.2021

МОДЕЛЮВАННЯ ФІЗИЧНИХ ПРОЦЕСІВ ПЕРЕТВОРЕННЯ ЕНЕРГІЇ В МАЛОГАБАРИТНИХ ВИХРОВИХ ЕНЕРГОРОЗДІЛЬНИКАХ

А. С. Кулік, С. М. Пасічник, Д. В. Сокол

Об’єктом вивчення в статті є вихровий ефект температурного поділу в потоці газу, що обертається та який виникає в малогабаритних вихрових енергороздільниках. У якості **предмета** вивчення виступають моделі, що описують фізичні процеси перетворення енергії в малогабаритних вихрових енергороздільниках як об’єктах автоматичного управління. **Метою** є отримання математичних моделей малогабаритного вихрового енергороздільника за експериментальними даними як об’єкта з нелінійною статичною характеристикою. **Задачі**: розробити тривимірну комп’ютерну модель малогабаритного вихрового енергороздільника, яка дозволить аналізувати параметри потоку газу і фізичні процеси перетворення енергії безпосередньо всередині об’єкта й отримати його статичні характеристики. Пропонується метод лінеаризації статичних характеристик на інтервалі вхідних і вихідних значень, який розширить робочий діапазон без втрати точності лінеаризації. Пропонується метод структурно-параметричної ідентифікації на основі експериментальних логарифмічних амплітудно-частотних характеристик, який дозволить для одного й того ж набору експериментальних точок обирати структуру математичної моделі різної складності в залежності від заданої точності. В результаті роботи сформована схема моделювання об’єкта автоматичного управління, що складається з блоку приводів, блоку датчиків і вихрового енергороздільника, з відображенням усіх отриманих режимів роботи. Використовуваними **методами** є: метод графічної лінеаризації, перетворення Лапласа, структурно-параметричної ідентифікації. Надані наступні **результати**: отримані комп’ютерна та лінеаризована математична моделі малогабаритного вихрового енергороздільника як об’єкта автоматичного управління, які відображають його властивості у часовій і частотній областях. Проведено порівняльний аналіз реакцій моделі та реального об’єкта на один і той самий вхідний сигнал. **Висновки**. Наукова новизна отриманих результатів полягає в наступному: 1) множинна графічна лінеаризація однієї статичної характеристики вихрового енергороздільника, що відрізняється від відомих відображенням перетворювальних властивостей в широкому діапазоні режимів функціонування; 2) структурно-параметричну ідентифікацію математичної моделі вихрового енергороздільника за допомогою відомих точок логарифмічних амплітудно-частотних характеристик з використанням інтерполяційного полінома та графіків його похідних.

Ключові слова: вихровий ефект; вихровий енергороздільник; комп’ютерна модель; графічна лінеаризація; частотні характеристики; ідентифікація; об’єкт автоматичного управління; схема моделювання; передавальна функція.

МОДЕЛИРОВАНИЕ ФИЗИЧЕСКИХ ПРОЦЕССОВ ПРЕОБРАЗОВАНИЯ ЭНЕРГИИ В МАЛОГАБАРИТНЫХ ВИХРЕВЫХ ЭНЕРГОРАЗДЕЛИТЕЛЯХ

А. С. Кулик, С. М. Пасичник, Д. В. Сокол

Объектом изучения в статье является вихревой эффект температурного разделения во вращающемся потоке газа, который возникает в малогабаритных вихревых энергоразделителях. В качестве **предмета**

изучения выступают модели, описывающие физические процессы преобразования энергии в малогабаритных вихревых энергоразделителях как объектах автоматического управления. **Целью** является получение математических моделей малогабаритного вихревого энергоразделителя по экспериментальным данным как объекта с нелинейной статической характеристикой. **Задачи**: разработать трехмерную компьютерную модель малогабаритного вихревого энергоразделителя, которая позволит анализировать параметры потока газа и физические процессы преобразования энергии непосредственно внутри объекта и получить его статические характеристики. Предлагается метод линеаризации статических характеристик на интервале входных и выходных значений, который расширит рабочий диапазон без потери точности линеаризации. Предлагается метод структурно-параметрической идентификации на основе экспериментальных логарифмических амплитудно-частотных характеристик, который позволит для одного и тоже набора экспериментальных точек подбирать структуру математической модели различной сложности в зависимости от заданной точности. В результате работы сформирована схема моделирования объекта автоматического управления, состоящая из блока приводов, блока датчиков и вихревого энергоразделителя, с отражением всех полученных режимов работы. Используемыми **методами** являются: метод графической линеаризации, преобразования Лапласа, структурно-параметрической идентификации. Предоставлены следующие **результаты**: получены компьютерная и линеаризованная математическая модели малогабаритного вихревого энергоразделителя как объекта автоматического управления, отражающие его свойства во временной и частотной областях. Проведен сравнительный анализ реакций модели и реального объекта на один и тот же входной сигнал. **Выводы**. Научная новизна полученных результатов заключается в следующем: 1) множественная графическая линеаризация одной статической характеристики вихревого энергоразделителя, отличающегося от известных отражением преобразовательных свойств в широком диапазоне режимов функционирования; 2) структурно-параметрическая идентификация математической модели вихревого энергоразделителя при помощи известных точек логарифмических амплитудно-частотных характеристик с использованием интерполяционного полинома и графиков его производных.

Ключевые слова: вихревой эффект; вихревой энергоразделитель; компьютерная модель; графическая линеаризация; частотные характеристики; идентификация; объект автоматического управления; схема моделирования; передаточная функция.

Кулік Анатолій Степанович – д-р техн. наук, проф., проф. каф. «Системи управління літальними апаратами», Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Пасічник Сергій Миколайович – канд. техн. наук, доцент. каф. «Системи управління літальними апаратами», Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Сокол Дмитро Вадимович – аспірант каф. «Системи управління літальними апаратами», Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Anatoliy Kulik – Doctor of Sciences (Engineering), Professor of the Department «Control Systems of Aircraft», National Aerospace University «Kharkov Aviation Institute», Kharkov, Ukraine,
e-mail: a.kulik@khai.edu, ORCID: 0000-0001-8253-8784.

Sergey Pasichnik – Candidate of Sciences (Engineering), associate professor of the Department «Control Systems of Aircraft», National Aerospace University «Kharkov Aviation Institute», Kharkov, Ukraine,
e-mail: snpasichnik@gmail.com, ORCID: 0000-0001-7016-8835.

Dmytro Sokol – PhD student at the Department «Control Systems of Aircraft», National Aerospace University «Kharkov Aviation Institute», Kharkov, Ukraine,
e-mail: d.sokol@khai.edu, ORCID: 0000-0003-0847-350X.