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IDENTIFICATION OF UAV MODEL PARAMETERS FROM FLIGHT AND COMPUTER EXPERIMENT DATA

The object of research in the article is various well-known approaches and methods of structural and parametric identification of dynamic controlled objects - unmanned aerial vehicles (UAVs). The subject of the research is the parameters of linear and nonlinear mathematical models of spatial and isolated movements, describing the dynamics and aerodynamic properties of the UAV and obtained both from the results of flight experiments and using computer object-oriented programs for 3-D UAV models. The goal is to obtain mathematical models of UAV flight dynamics in the form of differential equations or transfer functions, check them for reliability and the possibility of using them in problems of synthesis of algorithms for automatic control systems of UAVs. Tasks to be solved: evaluation of the analytical (parametric), direct (transient), as well as the identification method using the 3-D model of the control object. Methods used structural and parametric identification of dynamic objects; the determination of static and dynamic characteristics of mathematical models by the type of their transient process; the System Identification Toolbox package of the MatLab environment, the Flow Simulation subsystem of the SolidWorks software and the X-Plane software environment. The experimental parameters of UAV flights, as well as the results of modeling in three-dimensional environments, are the initial data for the identification of mathematical models. The following results were obtained: the possibility of analytical and computer identification of mathematical models by highly noisy parameters of the UAV flight was shown; the mathematical models of UAVs obtained after identification is reliable and adequately reproduce the dynamics of a real object. A comparative analysis of the considered UAV identification methods is conducted, their performance and efficiency are confirmed. Conclusions. The scientific novelty of the result obtained is as follows: good convergence, reliability and the possibility of using the considered identification methods for obtaining mathematical models of dynamic objects to synthesize algorithms for automatic control systems of UAVs is shown.

Keywords: *identification; transfer function; transient response; flight experiment; model parameters; mathematical model.*

Introduction

Determination of the aerodynamic parameters of the designed UAV at present is possible not only by blowing in the wind tunnel, but also by using software [1, 2]. Blowdowns in a wind tunnel are time-consuming: it is often required to create a reduced copy of the UAV under investigation; steering surfaces are in a static position; the operation and influence of the automatic flight control system on aerodynamic characteristics are not taken into account. In this paper, we use and compare the existing methods for identifying [3 - 5] parameters of dynamic objects using the example of a “B-kopter” designed and built SUAV of an aircraft scheme (Fig. 1). The SUAV is made according to the normal aerodynamic scheme with two traction motors that rotate two-bladed propellers. The motors rotate with their own servos relative to the transverse construction axis from the normal position (Fig. 1) to a parallel longitudinal axis (angle α_e).

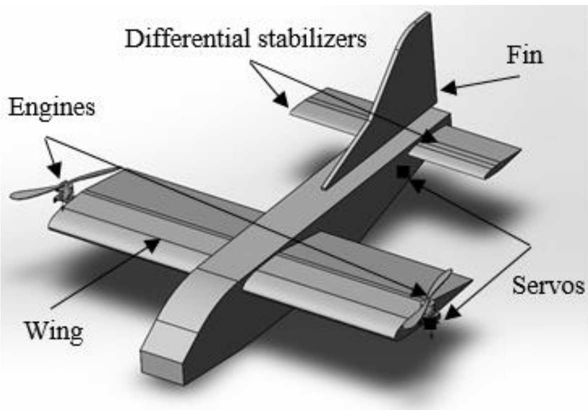

Fig. 1. SUAV “B-kopter”

The model is controlled by changing the module and the direction of the thrust vector, deviating the differential stabilizer and rudder. Researches are carried out for the purpose of reception dynamically similar mathematical model of a drone for the analysis of its characteristics of stability and controllability, synthesis of structure and laws of control of onboard ACS – autopilot.

1. Problem statement

The initial data for identifying UAV parameters can be its static or transient characteristics, according to which the aerodynamic and gear coefficients of the model must be obtained with maximum reliability, the moments of inertia are specified. The UAV is considered a solid body, the elasticity of the structure and screws is not taken into account. The criteria for assessing the quality of identification are such indicators [6] as overshoot σ, transient time tt, and the number of oscillations M.

2. Review of the literature

Theoretical bases of identification of systems [3] assume the presence of observations or measurements of parameters of the control object state vector, as which in this paper is selected SUAV "B-kopter". In most cases, the models of research UAV and small class [2] are designed and manufactured without using of calculations, preliminary construction of 3-D models and blowing in wind tunnels or virtual environments. At designing of similar objects the approach described in work [7] gives the best results. It is based on the consideration of all the features inherent to the flying model: the structural scheme, aerodynamics, power plant and the control system itself. Blows do not allow to obtain directly the dynamic components of aerodynamic coefficients, which depend on the angular velocities or bevel of the flow, which significantly reduces the reliability of the mathematical simulation of the UAV dynamics and the concept of flight characteristics of the model. The comparative analysis of possible identification methods at the stage of design and flight tests helps to clarify the model parameters and assess the adequacy of its dynamic properties. From various identification methods [3, 4] for the study were chosen: analytical (parametric), direct (by transient process) and with the use of MatLab on the results of the flight experiment, as well as identification by 3-D model of the control object.

3. Materials and methods

Parametric identification is made on the basis of the transition characteristic of the SUAV "B-kopter" by height (Fig. 2) with a stepped increase in the speed of rotation of engines, obtained as a result of flight experiment (the transient in ms on the abscissa axis and the altitude in m on the ordinate axis are plotted).

The process of height change allows to draw a conclusion that such movement is comparable to the dynamics of the oscillating link, but there are also higher frequency harmonics.

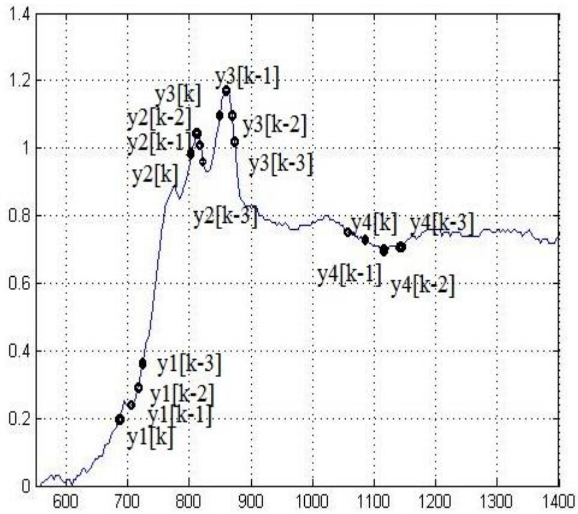

Fig. 2. Change in flight altitude

Consequently, the dynamics of movement of the model by height in the first approximation can be described, at least, by the third order differential equation in the presence of constant and velocity input influences by the formula (1):

$$a_1 \dddot{y} + a_2 \ddot{y} + a_3 \dot{y} + y = k(a_4 \dot{x} + x). \qquad (1)$$

We apply the Laplace transform [5] to equation (1) in the sample (2):

$$(a_1 s^3 + a_2 s^2 + a_3 s + 1)Y(s) = k(a_4 s + 1)X(s), \qquad (2)$$

then the transfer function of the SUAV in height is equal to formula (3):

$$W(s) = \frac{Y(s)}{X(s)} = \frac{k(a_4 + 1)}{a_1 s^3 + a_2 s^2 + a_3 s + 1}. \qquad (3)$$

It is necessary to find the coefficients a_i, $i = \overline{1,4}$ in (1) or (3). Let's select four points y_i in the transient graph (see, Fig. 2) at the current time [k]. Taking into ac-count the assigned T_0, let us define for them the values in the previous moments of time [k-1], [k-2],

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[k-3] and record equation (1) in the difference form by the formula (4):

$$\begin{aligned} & a_1 \frac{y[k]-3y[k-1]+3y[k-2]-y[k-3]}{T_0^3} + \\ & +a_2 \frac{y[k-1]-2y[k-2]+y[k-3]}{T_0^2} + \\ & +a_3 \frac{y[k-2]-y[k-3]}{T_0} + y[k-3] = \\ & = a_4 \frac{x[k-2]-x[k-3]}{T_0} + x[k-3]. \end{aligned} \qquad (4)$$

Substituting in (4) the values of y_1, y_2, y_3, y_4 allows us to reduce the search for the coefficients a_i to solve a system of equations with four unknowns [3], and then form the transfer function (3).

Identification in the MatLab environment was performed using the same experimental data on UAV flight altitude changes (see, Fig. 2), which are loaded into the System Identification Toolbox package (Fig. 3) by arrays or objects of the IDDATA class (Time domain, Frequency domain, Object). The data names and parameters [8] are entered, the order of the numerator polynomials is the first and the denominator polynomial is the third of the identifiable transfer function of the model by height (3) are set.

Synthesis of the mathematical model of “B-kopter” in the X-Plane environment [9] was carried out at the stage of UAV design, for which the 3D model was created (Fig. 4) with the obligatory indication of mass geometric data, steering surfaces, parameters and flight modes. In the environment of X-Plane on the formed 3D-model and the described connections of parameters s-model for Simulink MatLab [9] has been received.

In case of application of ACS for piloting or stabilization it is necessary to specify its functional communication with model parameters, then the 3D-model is integrated into Simulink MatLab environment.

Identification on transient process [6] is possible at absence of high-frequency components in dynamics of movement. However, real transients (see, Fig. 2) require approximation or filtering of high harmonics, which can be performed using algorithms of Kalman’s filtering [4, 5]. Direct identification was used to obtain the SUAV mathematical model by flight speed. Nonlinearities of transient characteristic were eliminated by linearization [6].

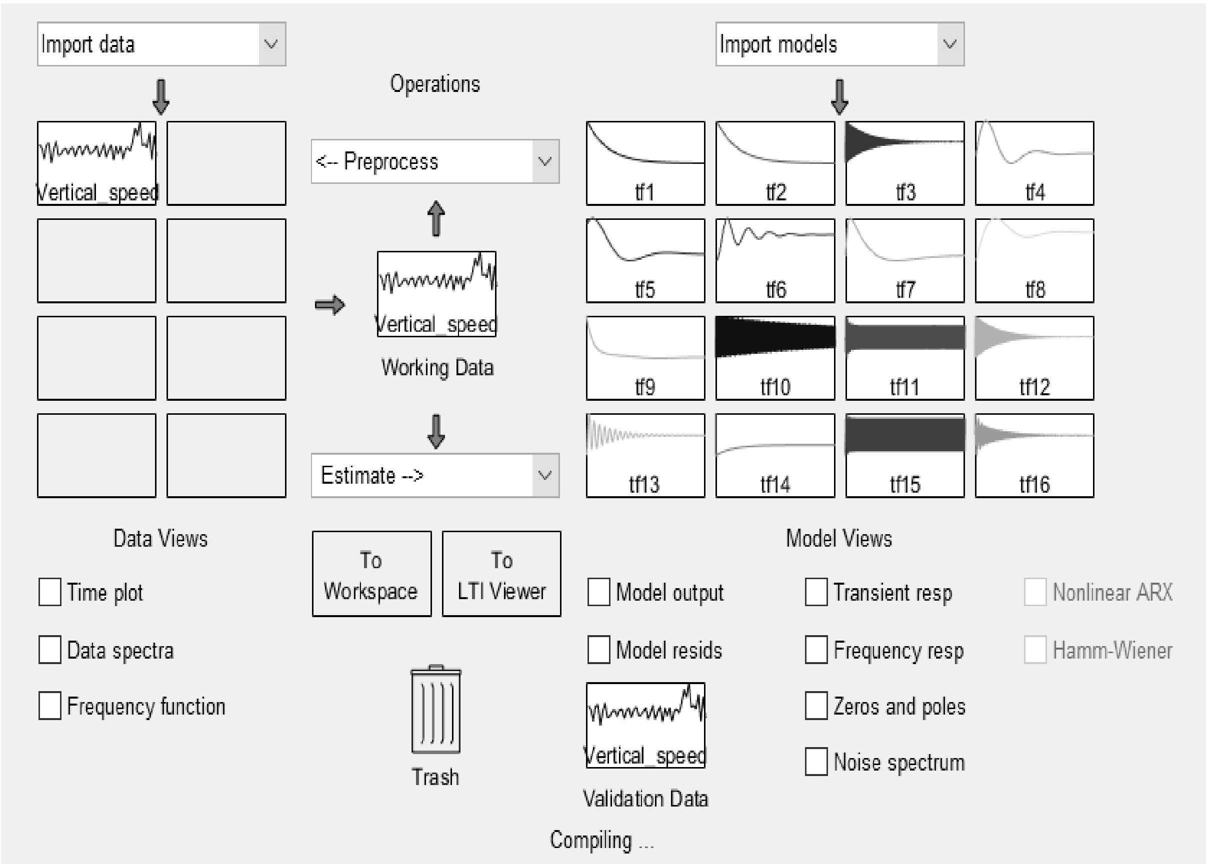

Fig. 3. System Identification Toolbox package

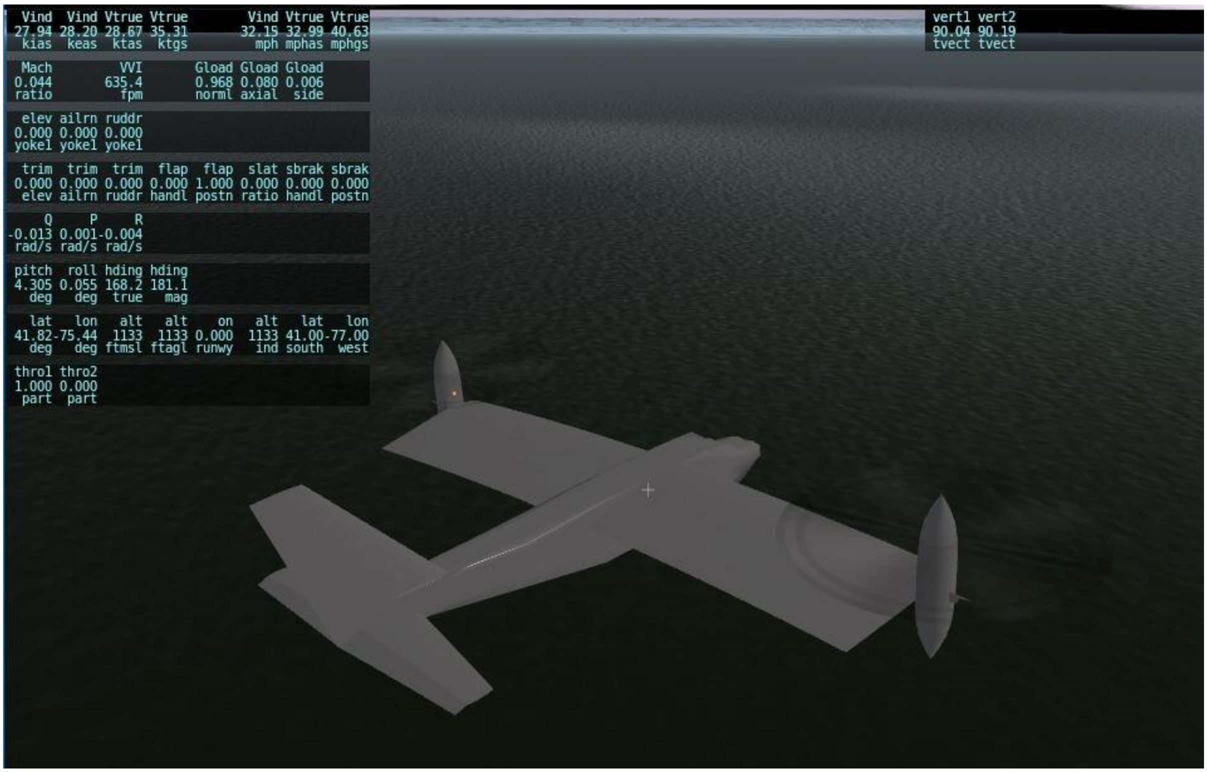

Fig. 4. 3D model in the X-Plane environment

4. Experiments

The flights of “B-kopter” were carried out in the modes of “hovering” (vertical take-off and holding the position coordinates in space) and flight with progressive speed.

The model motion parameters (speed, altitude, angles and angular velocities, accelerations, etc.) during experimental flights were recorded in the memory of the APM 2.5.8 controller and used to identify its characteristics. We used both manual control mode from the FS-T6 remote control and automatic control according to the program wired in APM 2.5.8. The flight diagram of the model was set in the Mission Planner environment [10], which allows the FPV Radio Telemetry to receive in real time all the information necessary for the experiment, including time charts (logs) of flight parameters. The thrust characteristic of the model engines, which determined the gear coefficient k of equation (1), was recorded in the starting state of the model using electronic scales.

5. Results and Discussion

In Fig. 5, a shows the H change logs in the “hover” mode, two “B-kopter” takeoffs are visible at 8-second intervals (the transient in $*10^3$ ms on the abscissa axis and the altitude in m on the ordinate axis are plotted).

The air velocity sensor V_x (blue line) and mini barometer H (green line) values at low altitude progressive motion are shown in Fig. 5, b (the transient in s on the abscissa axis and the altitude with the air velocity in m and m/s respectively on the ordinate axis are plotted).

In parametric identification, the transfer coefficient k in the equation (1) was determined by the traction static characteristic of engines “B-kopter” at the input PWM signal 550 ms and has the value k = 0.002. To calculate the values of the coefficients a_i we will assign the sampling period T_0 =0.2 s.

Let's determine the numerical values of the flight altitude (see, Fig. 2 and 5) at different moments of time:

$$y1[k]=0.2;\; y1[k-1]=0.215;\; y1[k-2]=0.25;$$
$$y1[k-3]=0.38;$$
$$y2[k]=0.98;\; y2[k-1]=1.025;\; y2[k-2]=1.05;$$
$$y2[k-3]=0.93;$$
$$y3[k]=1.1;\; y2[k-1]=1.18;\; y3[k-2]=1.08;$$
$$y3[k-3]=1.015;$$
$$y4[k]=0.77;\; y4[k-1]=0.74;\; y4[k-2]=0.75;$$
$$y4[k-3]=0.76;$$

substitute in equation (4), we obtain a system of equations with four unknowns in the equation (5):

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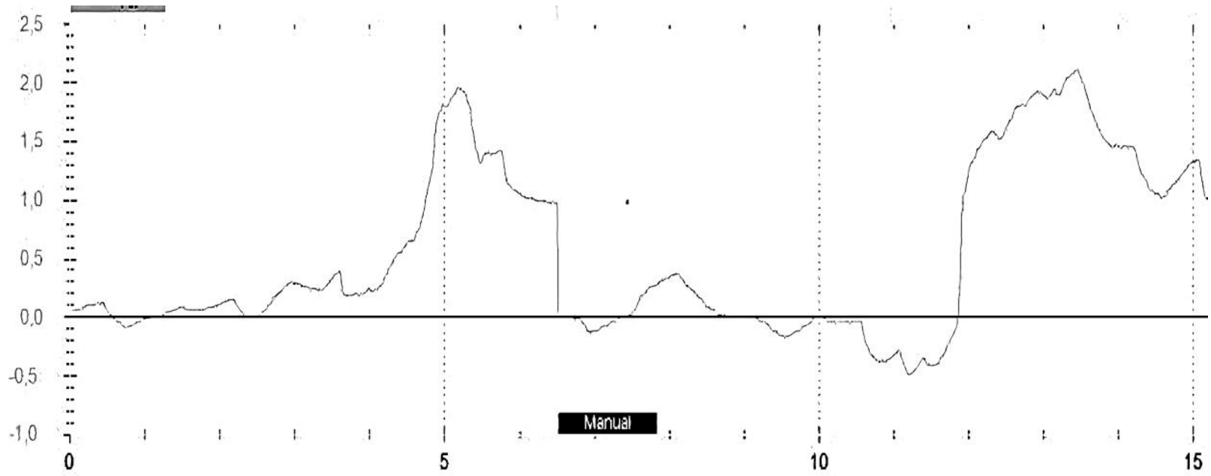
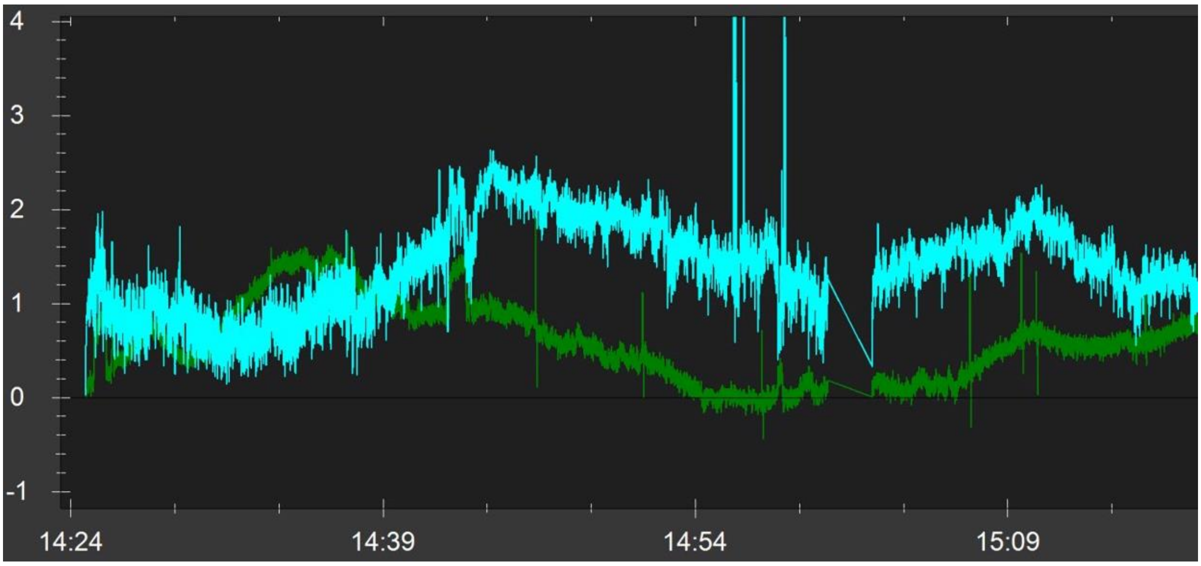


a



b

Fig. 5. Transients for: a – flight altitude in “hover” mode, b – air velocity sensor and mini barometer

$$\begin{cases} -9.375a_1 + 2.375a_2 - 0.65a_3 + 0.38 = \\ = -0.65a_4 + 0.76, \\ 15.625a_1 - 3.625a_2 + 0.6a_3 + 0.93 = \\ = 0.6a_4 + 0.76, \\ -26.875a_1 + 0.875a_2 + 0.325a_3 + 1.015 = \\ = 0.325a_4 + 0, \\ -1.25a_1 + 0.25a_2 + 0.05a_3 + 0.71 = \\ = 0.05a_4 + 0.76. \end{cases} \quad (5)$$

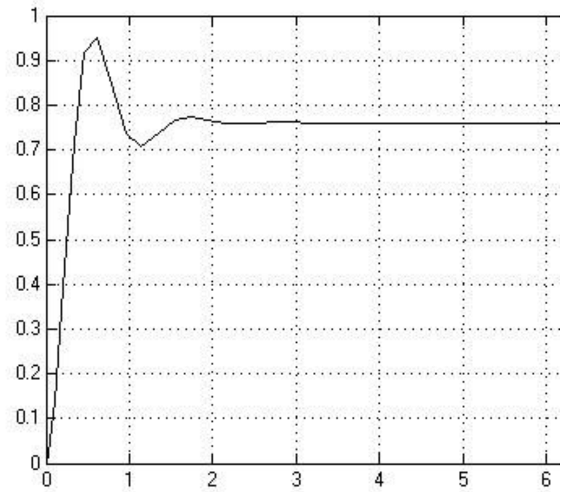
The solution of system (5) leads to numerical values of the coefficients a_1 = 17.78, a_2 = 84.58, a_3 = 649.26, a_4 = 598.3 in (1) and (3). The transfer function of the SUAV in the movement along the height during the setting action is equivalent to a third-order link with a boosting component:

$$W_H(s) = \frac{Y(s)}{X(s)} = \frac{598.3s + 1}{17.78s^3 + 84.58s^2 + 649.36s + 1}. \quad (6)$$

According to the transfer function (6) in Simulink MatLab the transient process of motion of the mathematical model “B-kopter” by height is obtained (Fig. 6, a) (the transient in $*10^2$ ms on the abscissa axis and the altitude in m on the ordinate axis are plotted).

The identification of the SUAV mathematical model in the MatLab environment using the System Identification Toolbox package [11] resulted in the desired transfer function of the model, obtained from the height characteristic transient data arrays (see, Fig. 2 and 6, a), with numerical parameters:

$$W_H(s)=\frac{Y(s)}{X(s)}=\frac{802.9s+1.85\cdot10^{-5}}{(3634.8s+1)}\cdot \cdot\frac{1}{(23315s+1)(22.16s+1)}. \quad (7)$$



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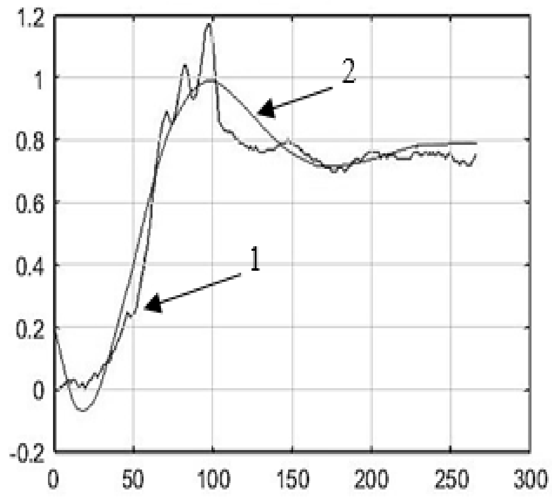

b

Fig. 6. Transients for: a – flight altitude in "hover" mode, b – air velocity sensor and minibarometer

The result of comparing the movement of "B-kopter" by height, obtained by simulating in Simulink MatLab identified model (7), with the experimental flight data is shown in Fig. 6, b (the transient in ms on the abscissa axis and the altitude in m on the ordinate axis are plotted). Here the line number 1 denote the experimental data, and the line number 2 indicates identification result. Coincidence of dynamics of the identified model (7) with the real one was 84%. Using the analytical identification method, the transient time was 2 s, whereas using the Matlab package it was 0.25 s. The overshoot rate σ was 26% and 23%, respectively. The oscillation rate M was 1.2 for analytical identification and 1 for Matlab.

Synthesis of the mathematical model of "B-kopter" in the X-Plane environment requires a full description of the 3D model of "B-kopter" (see, Fig. 4) with an indication of the functional relationship between the ACS and its parameters, it allowed to obtain the s-model in the X-Plane environment. After integration of structure of s-model in Simulink MatLab it is transformed to dynamically similar model (see, Fig. 7) which can be ap-plied to the analysis of characteristics of stability and controllability of the SUAV on various modes of flight on all parameters of movement specified in 3D-model.

Motion modeling by height of the obtained model (see, Fig. 6) showed a significant tightness of the output at a given height and the appearance of "small" oscillations (Fig. 8, a) (the transient in s on the abscissa axis and the altitude in ft on the ordinate axis are plotted).

The quality indices of the transition process in height when the autopilot was operating with the control laws synthesized during the identification process were obtained. The transient time was 18 s, the overshoot was 3%, while there was no oscillation.

Direct identification of the SUAV mathematical model by the transition characteristic of flight speed (see, Fig. 8, b) is possible after filtering and linearization of the corresponding flight speed of the logs, since the air speed sensor is very sensitive and its output signal contains a lot of noise. Here the blue line denote the experimental data, and the black line indicates result after filtration (the transient in ms on the abscissa axis and the air velocity in m/ms on the ordinate axis are plotted) in the Mission Planner environment [10] and then linearized (Fig. 9) (the transient in ms on the abscissa axis and the air velocity in m/ms on the ordinate axis are plotted).

Using the linearized transient, the SUAV transfer function was determined by speed when the angle of engine installation $\Delta\alpha_e$ was changed, similar to the aperiodic link in the equation (8):

$$W_{V_x}(s)=\frac{V_x(s)}{\Delta\alpha_e(s)}=\frac{k_V}{a_1s+1}=\frac{k_V}{T_Vs+1}, \quad (8)$$

and its parameters: transmission coefficient k_V = 0.2 at $\Delta\alpha_e$ = 5 deg, time constant T_V = 377 ms.

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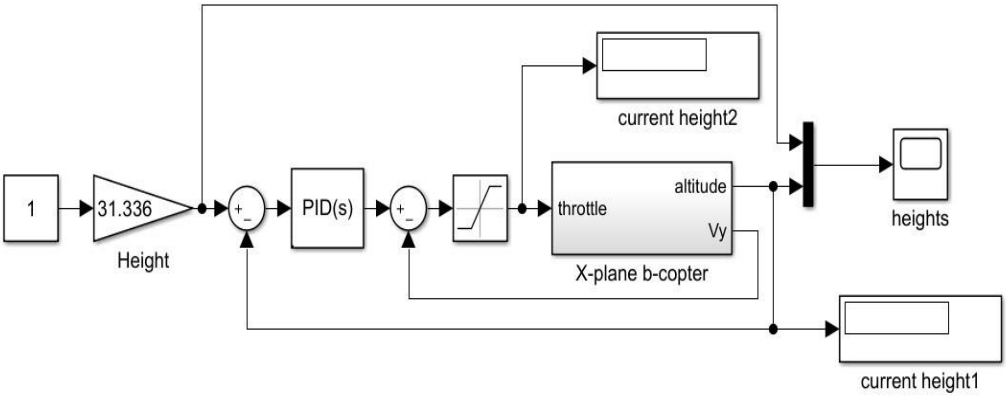
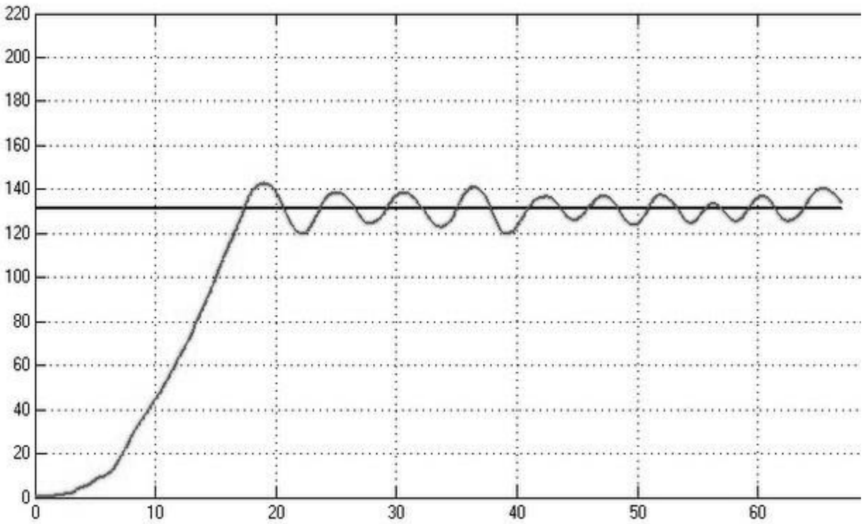
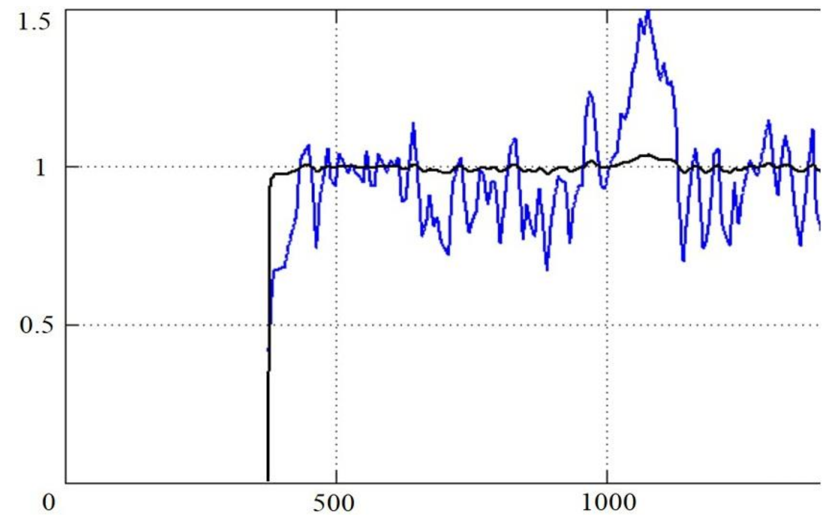


Fig. 7. s-model “B-kopter”



a



b

Fig. 8. Transients for: a – s-model “B-kopter” by H, b – speed V_x

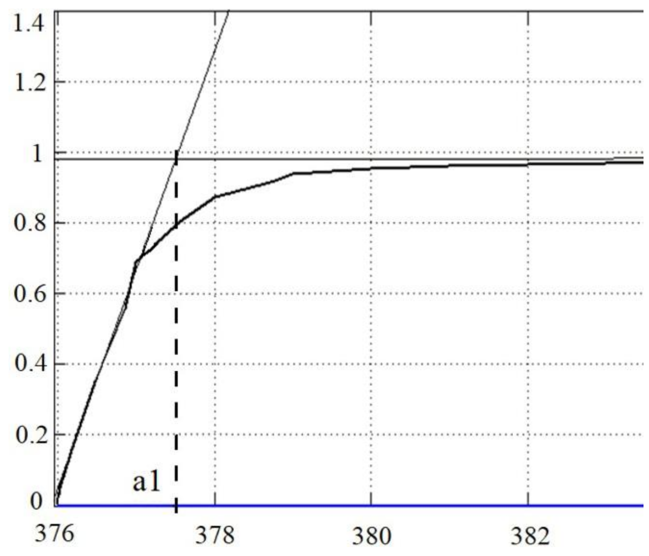


Fig. 9. Linearized transient response for “B-kopter” flight speed

For comparison, the identification of the transfer function parameters (8) was carried out according to the experimental data (see, Fig. 5) in Toolbox identification MatLab. The transient quality indicators of the model (8) obtained by direct identification and using Toolbox identification MatLab. When identifying through the MatLab package, the transient time was 12 s and the overshoot rate was 4%. With direct identification, the transient time was 5 s with no overshoot.

An analysis of the flight results (see, Fig. 5) shows that when identifying areas with clearly expressed deviations from the stabilized parameters, it is possible to identify and determine the transfer functions of mathematical models of SUAV motion dynamics (6), (7), (8). The good performance of model (7) compared to the model (6) obtained by the analytical method, with almost equal overshoot, is explained by the difference in identification algorithms, as well as the clear correspondence to the transition process (see, Fig. 2) of the points y_i. Despite the rather high coincidence (84%) of the transfer function (7) with flight data, analytical identification with a low order of the model is preferable to that performed in MatLab.

Obtaining a mathematical model of the “B-kopter” in the X-Plane environment is convenient and appropriate at the initial stages of design, when it is impossible or economically inexpedient to produce a real model and conduct a flight experiment. In addition, this identification method allows you to simultaneously synthesize the structure and algorithms of the control system in a nonlinear form (see, Fig. 7).

Transient identification is possible for isolated simple movements, the parameters of which do not contain high-frequency components or have been filtered. So the model in terms of flight speed (8) has better quality indicators compared to the one performed in MatLab.

Analysis of two flight experiments by height (see, Fig. 5, a) shows deterioration of transients - tpp = = 35-40 s, σ = 7-10 %, M = 2-3 as compared to modelling - tpp = 0.25-2 s, σ = 23-26 %, M = 1-1.2. This is due to the simplicity of the identifiable mathematical models, the lack of accounting for the operation of on-board equipment elements and the dynamics of engines and propellers.

Conclusions

The examples presented in the work of determining the parameters of linear models of SUAVs “B-kopter” using various identification algorithms showed the reliability of the obtained mathematical models, the possibility of their use for the analysis of dynamic properties. The choice of identification method is determined in each case. It is advisable to use various methods, comparing their results with a flight experiment. The mathematical models obtained in the work of isolated types of UAV motion are planned to be used to synthesize the control laws of onboard ACS, analyze the influence of the obtained algorithms on stability and controllability, the accuracy of stabilization of the angular position and a given flight path.

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research work [12], however were carried out for personal means of authors.

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ІДЕНТИФІКАЦІЯ ПАРАМЕТРІВ МОДЕЛІ БПЛА ЗА ДАНИМИ ЛЬОТНОГО ТА КОМП'ЮТЕРНОГО ЕКСПЕРИМЕНТІВ

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Об'єктом дослідження у статті є різні відомі підходи та методи структурної та параметричної ідентифікації динамічних керованих об'єктів – безпілотних літальних апаратів (БПЛА). **Предметом** дослідження є параметри лінійних та нелінійних математичних моделей просторового та ізольованих рухів, що описують динаміку та аеродинамічні властивості БПЛА, отримані як за результатами льотних експериментів, так і за допомогою комп'ютерних об'єктно-орієнтованих програм із використанням 3-D моделі БПЛА. **Мета** – отримати математичні моделі динаміки польоту БПЛА у вигляді диференціальних рівнянь або передавальних функцій, перевірити їх на предмет достовірності та можливості застосування задач синтезу алгоритмів систем автоматичного управління БПЛА. **Завдання**, що вирішуються: оцінка аналітичного (параметричного), прямого (перехідного), а також методу ідентифікації за допомогою 3-D моделі об'єкта управління. **Методи**, що використовуються: структурної та параметричної ідентифікації динамічних об'єктів; визначення статичних і динамічних характеристик математичних моделей на вигляд їх перехідного процесу; пакет System Identification Toolbox середовища MatLab, підсистема Flow Simulation програми SolidWorks, програмне середовище X-Plane. Експериментальні параметри польотів БПЛА, а також результати моделювання в тривимірних середовищах є вихідними даними для ідентифікації математичних моделей. Отримано такі **результати**: показана можливість аналітичної та комп'ютерної ідентифікації математичних моделей із сильно зашумленими параметрами польоту БПЛА, отримані після ідентифікації математичні моделі БПЛА є достовірними та адекватно відтворюють динаміку реального об'єкта. Проведено порівняльний аналіз досліджуваних методів ідентифікації БПЛА, підтверджено їх працездатність та ефективність. **Висновки**. Наукова новизна одержаних результатів полягає в наступному: отримана висока збіжність, надійність та можливість використання розглянутих методів ідентифікації для отримання математичних моделей динамічних об'єктів з метою подальшого синтезу алгоритмів систем автоматичного управління БПЛА.

Ключові слова: ідентифікація; передавальна функція; перехідний процес; льотний експеримент; параметри моделі; математична модель.

ИДЕНТИФИКАЦИЯ ПАРАМЕТРОВ МОДЕЛИ БПЛА ПО ДАННЫМ ЛЕТНОГО И КОМПЬЮТЕРНОГО ЭКСПЕРИМЕНТОВ

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Объектом исследования в статье являются различные известные подходы и методы структурной и параметрической идентификации динамических управляемых объектов – беспилотных летательных аппаратов (БПЛА). **Предметом** исследования являются параметры линейных и нелинейных математических моделей пространственного и изолированных движений, описывающие динамику и аэродинамические свойства БПЛА и полученные как по результатам летных экспериментов, так и с помощью компьютерных объектно-ориентированных программ по 3-D моделям БПЛА. **Цель** – получить математические модели динамики полета БПЛА в виде дифференциальных уравнений или передаточных функций, проверить их на предмет достоверности и возможности применения в задачах синтеза алгоритмов систем автоматического управления БПЛА. Решаемые **задачи**: оценка аналитического (параметрического), прямого (переходного), а также метода идентификации с помощью 3-D модели объекта управления. Используемые **методы**: структурной и параметрической идентификации динамических объектов; определение статических и динамических характеристик математических моделей по виду их переходного процесса; пакет System Identification Toolbox среды MatLab, подсистема Flow Simulation программы SolidWorks и программная среда X-Plane. Экспериментальные параметры полетов БПЛА, а также результаты моделирования в трехмерных средах выступают исходными данными для идентификации математических моделей. Получены следующие

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результаты: показана возможность аналитической и компьютерной идентификации математических моделей по сильно зашумленным параметрам полета БПЛА, полученные после идентификации математические модели БПЛА являются достоверными и адекватно воспроизводят динамику реального объекта. Проведен сравнительный анализ рассматриваемых методов идентификации БПЛА, подтверждена их работоспособность и эффективность. **Выводы**. Научная новизна полученных результатов заключается в следующем: показана хорошая сходимость, надежность и возможность использования рассмотренных методов идентификации для получения математических моделей динамических объектов в целях синтеза алгоритмов систем автоматических управления БПЛА.

Ключевые слова: идентификация; передаточная функция; переходный процесс; летный эксперимент; параметры модели; математическая модель.

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