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Original study article

Mathematical model of the hovercraft lift system

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ABSTRACT

BACKGROUND: Currently, hovercrafts are used worldwide thanks to their amphibian capabilities and mobility at water and slightly prepared areas with low supporting properties. Whereas, in practice, hovercrafts have two main systems ensuring motion, lift and traction which can be combined (operating from a common source of mechanical energy) as well as separated. This paper considers a hovercraft with separated lift and traction systems. The lift system of this hovercraft consist of piston diesel internal combustion engine (ICE), hydrostatic transmission, axial fans, feeding channel and an air-cushion plenum. The considered variant is chosen because hydrostatic transmission has a number of sufficient advantages in comparison with mechanical transmission with universal shafts and pulley drives, widely used at present time. The paper considers the open plenum lift system.

AIM: Development of the combined mathematical model of the hovercraft lift system consisting of piston diesel ICE, hydrostatic transmission and a fan supplying air into the air-cushion plenum.

METHODS: Using the MATLAB/Simulink environment, the engine power adjustment at hovercraft motion on various ground surfaces is studied with regard to increasing the efficiency of the fan and the whole system. Analytical scheme of the system is given, acceptable transient characteristics are obtained. Efficiency and range of optimal operation of the Sauer-Danfoss pump and hydraulic motor are estimated. The process of hovercraft adjustment from the established mode to a new state when motion condition change is considered.

RESULTS: According to the simulation results, there is influence of the income control signal (adjustment parameter of engine operation modes) and disturbance signal (pressure change coefficient that defines properties of ground surface) on parameters describing the hovercraft motion.

CONCLUSION: The developed mathematical model helps to choose and evaluate adjustment parameters of engine operation modes at hovercraft motion on various ground surfaces, to analyze and to improve the system energy efficiency.

Keywords: hovercraft; lift system; internal combustion engine; hydrostatic transmission; energy efficiency; mathematical model.

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Оригинальное исследование

Математическая модель подъёмной системы судна на воздушной подушке

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АННОТАЦИЯ

Введение. В настоящее время суда на воздушной подушке (СВП) широко применяются во всём мире благодаря своей амфибийной способности и проходимости на водных и элементарно подготовленных площадках с низкой несущей способностью. При этом на практике СВП имеют две главные системы, обеспечивающие движение: подъёмную и тяговую, которые могут быть как объединённые (работающие от одного источника механической энергии), так и раздельные.

В данной статье рассматривается СВП, имеющее раздельные подъёмную и тяговую системы. При этом подъёмная система такого СВП состоит из поршневого дизельного двигателя внутреннего сгорания (ДВС), гидравлической трансмиссии гидрообъёмного типа, осевых вентиляторов, канала подвода и камеры образования воздушной подушки. Рассматриваемый вариант обусловлен тем, что гидрообъёмная трансмиссия обладает рядом существенных преимуществ перед механической трансмиссией с карданными валами и ремёнными передачами, широко применяемой в настоящее время. В статье рассматривается камерная схема образования воздушной подушки.

Цель исследования — разработка совместной математической модели подъёмной системы СВП, состоящей из поршневого дизельного ДВС, гидрообъёмной трансмиссии и вентилятора, подающего воздух в секции воздушной подушки.

Методы. В среде MATLAB/SIMULINK анализируется регулирование мощности двигателя при движении судна на разных опорных поверхностях с точки зрения увеличения КПД вентилятора и всей системы. Приведена расчётная схема системы, получены приемлемые переходные характеристики. Оцениваются КПД, диапазон оптимальной работы насоса и гидромотора Sauer-Danfoss. Рассматривается процесс регулирования СВП от установившегося режима до нового состояния при изменении условий движения.

Результаты. По результатам моделирования показано влияние входного управляющего сигнала (параметра регулирования режимов работы двигателя) и возмущающего сигнала (коэффициента перепада давления, определяющего свойства опорной поверхности) на параметры, характеризующие движение судна.

Заключение. Разработанная математическая модель позволяет выбирать и оценивать параметры регулирования режима работы двигателя при движении судна на разных поверхностях, анализировать и улучшать энергоэффективность системы.

Ключевые слова: судно на воздушной подушке; подъёмная система; двигатель внутреннего сгорания; гидравлическая трансмиссия; энергоэффективность; математическая модель.

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INTRODUCTION

Currently, hovercrafts are widely used worldwide because of their amphibious capabilities and mobility on water and slightly prepared sites with low load-supporting properties. Vessels of this class are self-supported over ground or water surfaces using an air cushion (AC) created by marine-type fans. Approximately one-third of the total power produced by the hovercraft power plant is consumed on creating this AC, which ensures the lifting of the vessel's main body.

Modern hovercrafts are classified according to the following main features, which reflect the general structure and operating principles of hovercrafts:

- degree of interaction between vessel and surface in the hovering and moving modes;
- AC formation;
- structure of the AC enclosure [1].

In practice, modern hovercrafts are equipped with two main systems, namely the lifting and traction systems. These systems can be either operated together (i.e., obtaining mechanical energy from a single source) or separately. The traction system is used to create an airflow astern, enabling the hovercraft to move forward. The lifting system is used to provide airflow under the hovercraft body, enabling the hovercraft to float above a surface. The hovercraft traction system is mainly based on dynamic air pressure, whereas the lifting system is mainly based on static pressure, which is determined by the design of the lifting system, its size, and its method of control.

In a hovercraft, where its two main systems are operated separately, the lifting system has several advantages such as simple design, control (including balancing of the vessel) as well as maintenance and repair. However, this hovercraft type requires two independent sources of mechanical energy; one for the lifting system and one for the traction system.

In this hovercraft type, a reciprocating diesel internal combustion engine (ICE) is used as the source of mechanical energy [2, 3].

The main issues that need to be addressed when designing a hovercraft include a reduction in the power consumed on creating the AC, a reasonable ratio of the hover height and vessel size, and improvement in the AC control system during the hovercraft movement.

The objective of this study is to develop a mathematical model of a hovercraft lifting system, which consists of an ICE, a hydrostatic transmission, and a fan that supplies air to the AC (Fig. 1).

METHODS AND MATERIALS OF RESEARCH

Mathematical description of the hovercraft fan-air cushion system

For a hovercraft to rise above a surface, air pressure must be created under its bottom as follows:

$$p_{п} = G/S_{п} ,$$

where G is the hovercraft mass and S_c is the AC area.

The fan creates an airflow of pressure

$$p_a = K_d \cdot p_c ,$$

where K_d is a coefficient representing the pressure drop from the fan to the AC and depends on the airflow, hovercraft design, and surface properties.

The characteristics of the OV-109 fan selected for this study are presented in Fig. 2. The construction of this fan was based on its experimentally verified dimensionless characteristics [4].

When the vessel moves above different surfaces, the pressure loss from the fan to the AC varies, depending

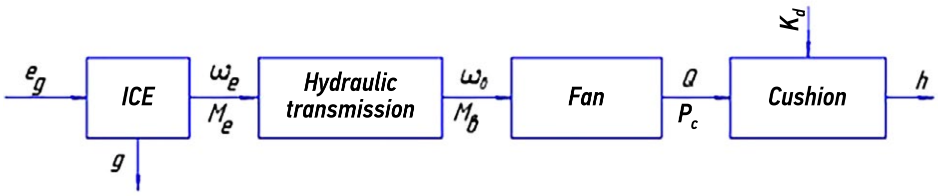

Fig. 1. Principal block diagram of the hovercraft lift system: e_g — adjustment parameter of the engine operating mode; g — cyclic fuel delivery; ω_e, M_e — rotation velocity and torque transmitted from the engine; $\omega_в$, $M_в$ — rotation velocity and torque of the fan; h — hovercraft lift height; Q — air flow rate; p_c — excessive pressure in the air-cushion; K_p — the hovercraft motion conditions coefficient.

Рис. 1. Принципиальная блок-схема системы подъёма СВП: e_g — параметр регулирования режима работы двигателя; g — цикловая подача топлива; ω_e, M_e — скорость вращения и крутящий момент, передаваемый от двигателя; $\omega_в$, $M_в$ — скорость вращения и крутящий момент вентилятора; h — высота подъёма СВП над опорной поверхностью; Q — расход воздуха; p_c — избыточное давление в подушке; K_p — коэффициент, учитывающий условия движения СВП.

on the surface properties. However, the air pressure in the AC must be maintained at a specific value despite the change in pressure loss $p_a - p_c = \Delta p$ (p_c: pressure under AC), which also leads to a change in p_a. In addition, the vessel weight may change due to the fuel consumed and cargo carried. At the same time, p_c changes, causing a change in p_a. Thus, the change in p_a is equivalent to the change in K_d; this is modeled as a disturbing signal [5].

During mathematical modeling, we assumed that the pressure and air density over the volume of each AC cavity are evenly distributed, and the air compression processes are polytropic.

Mathematical model of the ZMZ-514 diesel engine

In this study, a ZMZ-51432.10 CRS reciprocating diesel engine that meets the technical requirements was used in the hovercraft lifting system.

The engine power, efficiency, acceleration response, reliability, and other parameters were appropriately adjusted to ensure the required performance under specific operating conditions.

Due to the ICE characteristics, the selection of such an engine for transport systems is usually based on the required maximum power. However, in our case, the engine uses its maximum power only for a short period because it operates at partial loads. Therefore, the ICE power must be appropriately adjusted to achieve high efficiency in partial-load mode operation.

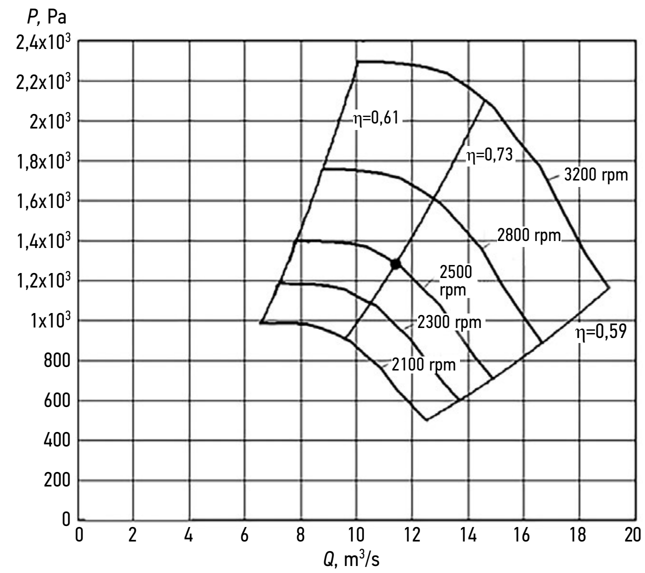

Fig. 2. Head and rate characteristic of the OV-109 fan at various rotation velocities: point I — the required operation point; η — fan efficiency.

Рис. 2. Напорно-расходная характеристика вентилятора ОВ-109 при разных частотах вращения: точка I — требуемая точка работы; η — КПД вентилятора.

In this study, the diesel engine was adjusted by adjusting the cyclic fuel supply [6, 7].

Using the DIESEL-RK program and a method for identifying the engine characteristics, the relationship between the torque M_e, the angular speed of rotation ω_r of the engine shaft, and the engine operation control parameter e_g is given as follows [8]:

$$M_e = A_0 + A_1 \cdot \omega_e + A_2 \cdot \omega_e^2 + A_3 \cdot \omega_e^3 + A_4 \cdot \omega_e^4 \,, \quad (1)$$

where the corresponding coefficients are determined as follows:

$$\begin{cases} A_0 = -1099{,}56e_g - 460{,}05; \\ A_1 = 20{,}46e_g + 6{,}94; \\ A_2 = -0{,}114e_g - 0{,}0391; \\ A_3 = 0{,}00028e_g + 9{,}76E-5; \\ A_4 = -2{,}58E-7e_g - 9{,}09E-8. \end{cases} \quad (2)$$

Note that the error of the mathematical description of the ICE operation corresponds to R^2 values in the 0.977–0.986 range for $M_e = f(\omega_e)$ and in the 0.971–0.984 range for $A_i = f(e_g)$, which are considered satisfactory in this study.

In equation (2), $e_g = \frac{N}{N_{\max}}$ is the parameter used for adjusting the engine operating mode, where N is the instantaneous engine power and $N_{\max}$ is the maximum engine power. The range of the e_g values used in modeling the engine operating modes was $0.4631 \le e_g \le 0.9539$.

The mathematical description of the engine operation enables us to obtain the engine characteristics within acceptable deviations from the initial parameter values and can be used in the developed mathematical model of the hovercraft lifting system along with the mathematical models of other elements of this system [9].

Mathematical model of hydrostatic transmission of the hovercraft lifting system

Hydrostatic transmission has the following significant advantages over mechanical cardan-shaft and belt transmissions, which are widely used nowadays:

- reliability, high performance, smooth operation, high energy intensity, convenient installation, and easy maintenance.
- reliable operation at extreme temperatures (–50°C to + 50°C).

A schematic of the hydrostatic transmission of the hovercraft lifting system is shown in Fig. 3. This type of transmission consists of three nonadjusted axial piston hydraulic components, namely, a main pump (*2*) and two hydraulic motors (*5*). The pump shaft is driven by the ICE (*1*). The pump is connected to the hydraulic motors (*5*) via two pipelines (*4*). The hydraulic motor shafts are connected to their corresponding AC fans (*6*).

The leaks of the operating fluid are compensated by the compensation pump (*3*), which is driven by the main pump shaft. When the pressure in one of the pipelines drops below a permissible level, the corresponding compensation valve (*7*) opens and lets liquid pass under pressure through the pressure line of the compensation pump until the required pressure level is restored in the pipeline. Afterward, the compensation valve closes under pressure in the pipeline.

In the development of the hydrostatic transmission mathematical model, equations describing the flow balance at the node points of the hydraulic system (considering fluid compressibility), differential equations describing changes in the torque of the shafts of the engine–pump and hydraulic motor–fan systems, and equations describing mechanical energy losses in the hydraulic system [10–12] were used.

RESULTS AND DISCUSSION

Further studies were conducted to analyze the accuracy of the developed mathematical model. For this purpose, we considered the transient processes associated with the regulation of the hovercraft lifting system when the hovercraft movement conditions change from one established mode to another.

The hovercraft movement mode was adopted as the base mode, which was characterized by the following parameters: fan rotation speed $n_r = 2500$ rpm; AC pressure $p_c = 853$ Pa, hovercraft airflow rate $Q = 22.76$ m^3/s, and $K_d = 1.5$.

These parameters were used as the initial conditions for the transient processes.

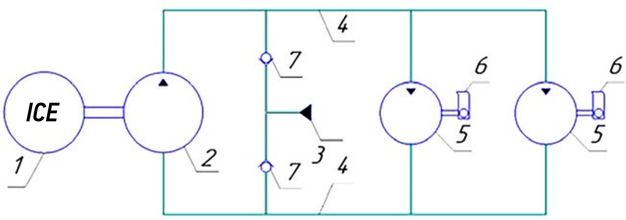

Fig. 3. Principal scheme of the hydrostatic transmission of the hovercraft lift system: *1* — the ZMZ-51432.10 CRS engine; *2* — the Danfoss non-adjustable axial piston pump; *3* — flow from a feeding pump; *4* — a hydraulic line; *5* — the Danfoss non-adjustable axial-piston hydraulic motor; *6* — an axial fan; *7* — a feeding valve.

Рис. 3. Принципиальная схема гидрообъёмной трансмиссии системы подъёма СВП: *1* — двигатель ЗМЗ-51432.10 CRS; *2* — нерегулируемый аксиально-поршневой насос *Danfoss*; *3* — поток, поступающий от подпиточного насоса; *4* — трубопровод; *5* — нерегулируемый аксиально-поршневой гидромотор *Danfoss*; *6* — осевой вентилятор; *7* — подпиточный клапан.

Hovercraft control by adjusting the engine operating mode

During modeling, e_g was considered as the input (control) signal; K_d was considered as a disturbing signal caused by the change in surface properties during the hovercraft movement.

The following two cases were considered:

1) K_d changes from 1.5 to 1.1;
2) K_d changes from 1.5 to 1.7.

MATLAB Simulink was used to simulate the hydraulic drive. The simulation results are presented in the form of transient processes (Figs. 4 and Fig. 5).

In case 1, a change in pressure at second 1 of the simulated process (Fig. 4) due to a change in K_d caused a change in the output signals presented in Fig. 4, namely, the hovercraft height above the surface, the rotational speed of the hydraulic motor and fan shafts, the rotational speed of the engine and pump shafts, the efficiency of the fan, pump, hydraulic motor, and engine power.

The steady-state values of the system design parameters when K_d changes from 1.5 to 1.1 in the absence of control are presented in Table 1; the parameter values when using the proposed control system are presented in line engine control EC (engine control).

The analysis showed that when K_d decreases from 1.5 to 1.1, which corresponds to the hovercraft movement from a high-K_d surface to a low-K_d surface, the airflow in AC increases, resulting in an increase in the hovercraft height h above the surface. This leads to a change in the fan operating point, which departs from its highest efficiency (the fan efficiency decreases from 71.65% to 64.59%). A decrease in e_g from 0.68 to 0.51 at second 4 of the simulated process causes a decrease in the amount of fuel consumed by the engine, leading to a decrease in the rotation speed of the pump and hydraulic motor shafts. As a result, the airflow in AC decreases, and the hovercraft height decreases to its initial value. This enables the hovercraft to save energy under easier conditions than those corresponding to $K_d = 1.5$. The fan operating point also returns to its initial highest efficiency value.

In case 2, when the surface properties change during the hovercraft movement, the pressure in AC increases due to an increase in K_d from 1.5 to 1.7. The simulation results are presented in the form of transient processes shown in Fig. 5.

The analysis showed that when K_d increases from 1.5 to 1.7, which corresponds to the hovercraft movement from a low-K_d surface to a high-K_d surface, the airflow in AC decreases, resulting in a decrease in the hovercraft height h above the surface. This leads to a change in the fan operating point, which departs from its highest efficiency (the fan efficiency decreases from 71.65% to 63.72%). An increase in e_g from 0.68 to 0.75 at second 4 of the simulated process causes an increase in

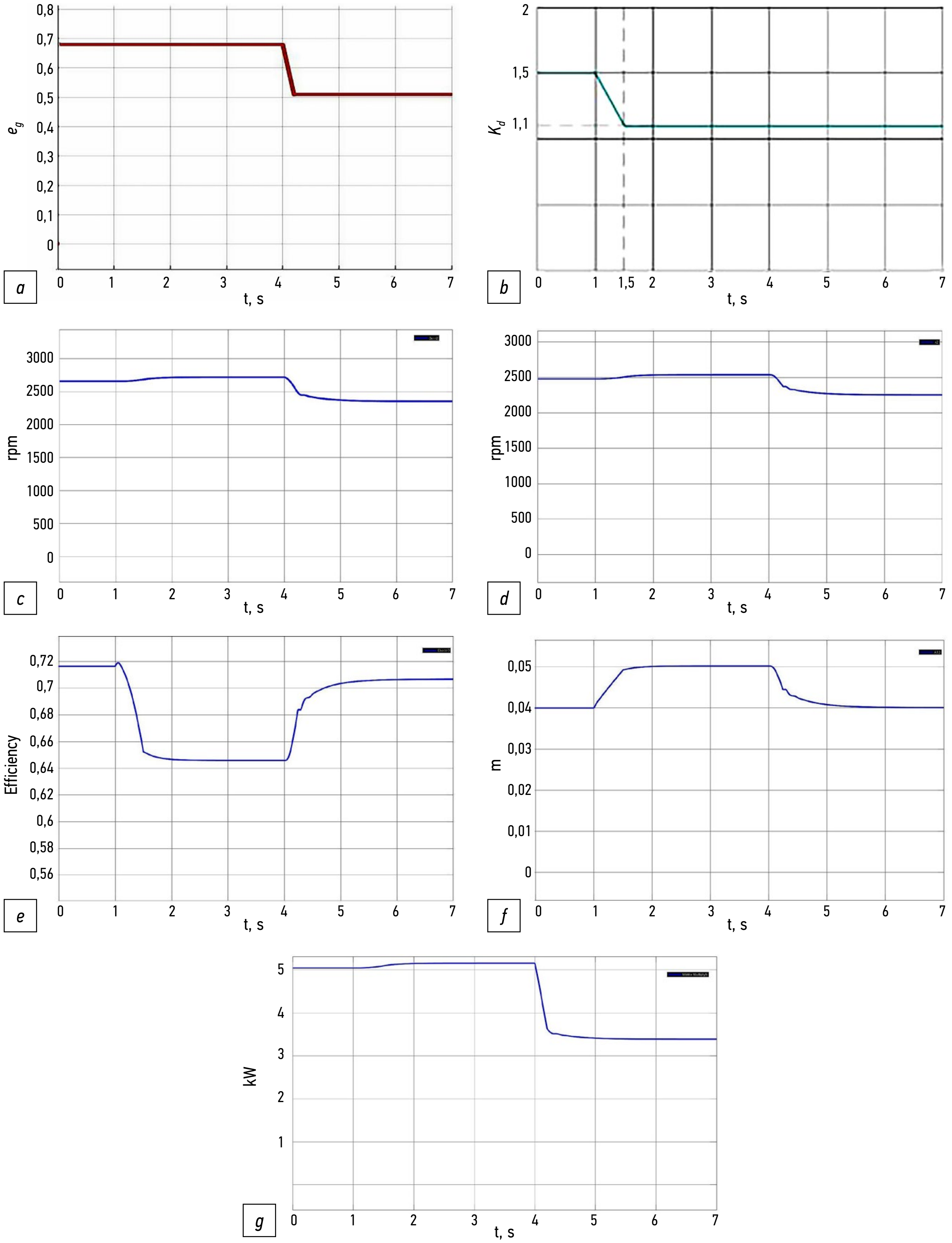

Fig. 4. Transient processes at K_d decreasing: *a* — engine adjustment parameter e_g; *b* — signal K_d; *c* — engine rotation velocity $n_д$; *d* — fan rotation velocity $n_в$; *e* — fan efficiency $\eta_в$; *f* — hovercraft height above the ground h; *g* — engine power N_g.

Рис. 4. Переходные процессы при уменьшении K_d: *a* — параметр регулирования двигателя e_g; *b* — сигнал K_d; *c* — частота вращения двигателя $n_д$; *d* — частота вращения вентилятора $n_в$; *e* — КПД вентилятора $\eta_в$; *f* — высота СВП над опорной поверхностью h; *g* — мощность двигателя N_g.

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Table 1. The system 1 parameters

Таблица 1. Параметры системы-1

K_d	e_g	$n_д$, rpm	p_c, MPa	n_r, rpm	$\eta_н$, %	$\eta_г$, %	$\eta_в$, %	h, mm	N_g, kW
1,5	0,68	2659	25,44	2479	88,98	89,10	71,65	39,95	50,47
1,1	0,68	2719	25,41	2537	88,98	89,10	64,59	50,16	51,55
РД	0,51	2361	19,07	2256	88,91	89,67	70,68	40,06	33,89

the amount of fuel consumed by the engine, leading to an increase in the rotation speed of the pump and hydraulic motor shafts. As a result, the airflow in AC increases, and the hovercraft height increases to its initial value, allowing the hovercraft to improve its ability to move under new conditions. The fan operating point also returns to its initial highest efficiency value. It is evident that in case 2, the fuel consumption increases to enable the hovercraft to operate under heavier conditions than those corresponding to K_d = 1.5.

The steady-state values of the system design parameters when K_d changes from 1.5 to 1.7 are presented in Table 2 after adjusting the operating mode.

CONCLUSION

We developed a mathematical model of the hydraulic transmission and fan of a hovercraft based on experimental data. The model employs real calculation methods and produces fairly accurate results that are significant in practice. Additionally, it can be used for the selection and evaluation of the optimal speed of the hydraulic motor and fan shafts when the hovercraft moves above specific surfaces by employing an engine operation control parameter. Furthermore, it can be used to monitor changes in the pump and hydraulic motor efficiencies as well as changes in the hydraulic transmission parameters.

The simulation of the engine, hydraulic transmission, and the fan that supplies air to AC enables us to determine the system characteristics. It also enables us to study the changes in parameters and control methods as well as to assess the impact of a component on other components and the operation of the entire system, resulting in reduced design time and cost.

ADDITIONAL INFORMATION

Authors' contribution. Van Hoa Nguyen — search for publications, writing the text of the manuscript; A.V. Lepeshkin — scientific supervision, editing the text of the manuscript, approval of the final version; N.G. Sosnovsky — scientific supervision, editing the text of the manuscript, approval of the final version. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

Competing interests. The authors declare that they have no competing interests.

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Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

Table 2. The system 2 parameters

Таблица 2. Параметры системы-2

K_d	e_g	$n_д$, rpm	P_c, MPa	$n_в$, rpm	$\eta_н$, %	$\eta_г$, %	$\eta_в$, %	h, mm	N_g, kW
1,5	0,68	2659	25,44	2479	88,98	89,10	71,65	39,95	50,47
1,7	0,68	2724	25,40	2542	88,98	89,10	63,72	32,07	51,63
РД	0,75	2829	28,08	2610	88,88	88,79	70,91	40,63	59,02

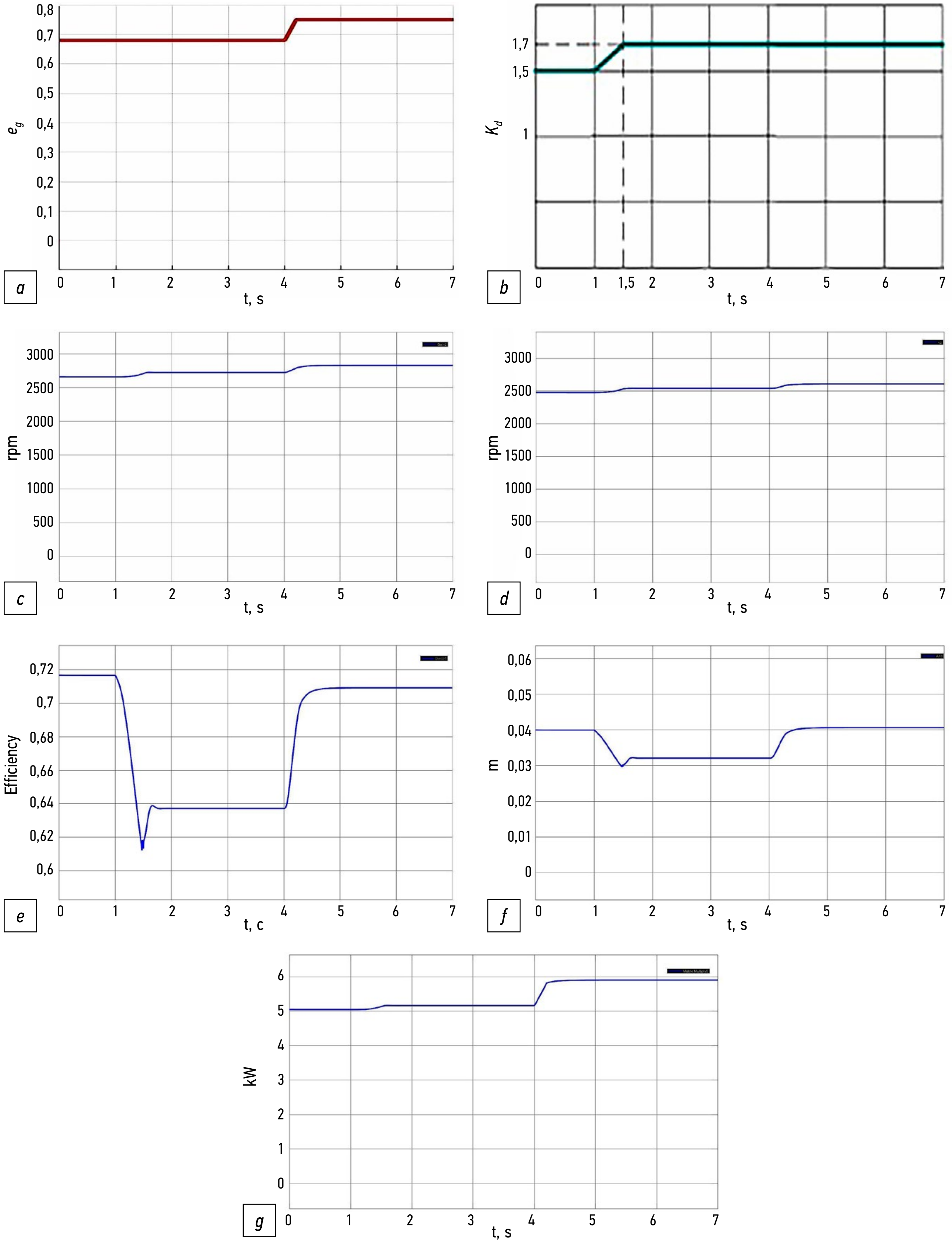

Fig. 5. Transient processes at K_d increasing: *a* — engine adjustment parameter e_g; *b* — signal K_d; *c* — engine rotation velocity $n_д$; *d* — fan rotation velocity $n_в$; *e* — fan efficiency $\eta_в$; *f* — hovercraft height above the ground h; g — engine power N_g.

Рис. 5. Переходные процессы при увеличении K_d: *a* — параметр регулирования двигателя e_g; *b* — сигнал K_d; *c* — частота вращения двигателя $n_д$; *d* — частота вращения вентилятора $n_в$; *e* — КПД вентилятора $\eta_в$; *f* — высота СВП над опорной поверхностью h; g — мощность двигателя N_g.

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