The object of the study is the process of forming force loads during the supply of fire extinguishing agents through a fire hose held by an unmanned aerial vehicle. The problem that was solved in the study is the lack of calculation models of the joint action of the jet stream and the tension of the vertical hose line on a multirotor unmanned aerial vehicle during high-altitude fire extinguishing, which complicates the selection of the hose mounting parameters and compensation for destabilizing moments. Empirical data were obtained on the distribution of reactive and static forces during the supply of fire extinguishing agents in the fastening nodes of the hose line suspension system and the fire hose using the developed installation at altitudes of 30-50 m. It was established that with increasing altitude, primarily the static load on the suspension system increases. After stabilization of the supply mode, the value of the force F_6 is 340–350 N at an altitude of 30 m, 366–390 N at an altitude of 40 m, and 396–428 N at an altitude of 50 m. The reactive force F_5 had lower values, but increased with increasing pressure and nozzle diameter. At an altitude of 40 m, the force F_5 was 33–45 N. At 50 m, for a nozzle with a diameter of 5 mm, it was 34–49 N, for a nozzle with a diameter of 6 mm, it was 54 N, and for a nozzle with a diameter of 7 mm, it was 57 N. The highest loads were recorded at a pressure of 8 bar and nozzle diameters of 6–7 mm. The results show that the altitude determines mainly the static load, and the reactive force depends on the pressure and nozzle diameter. For the mathematical description, a full factorial experiment was used with the factors of the time of supply of fire extinguishing agents, pressure, and nozzle diameter. Interpolation regression relationships for reactive forces F_1–F_5 were obtained. The tension force F_6 is described by a quadratic model taking into account time and altitude. A feature of the study is a comprehensive assessment of the jet reactive force, tension force and loads at the barrel fixation points. The obtained patterns are significant in view of the increasingly widespread integration of unmanned aerial vehicles into the firefighting industry. The results can be used to substantiate the design parameters of unmanned aerial vehicles during their design

Keywords: unmanned aerial vehicle, firefighting, force loads, reactive force, fire extinguishing agent

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THE ESTABLISHMENT OF THE PATTERNS OF FORCE LOADS ON AN UNMANNED AERIAL VEHICLE BASED ON THE PARAMETERS OF FIRE-EXTINGUISHING AGENT SUPPLY THROUGH A FIRE NOZZLE

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1. Introduction

The use of unmanned aerial vehicles (UAVs) in the field of fire safety is a promising direction in the development of emergency and rescue equipment. UAVs can be used to monitor the fire situation, detect ignition sources, as well as deliver and supply fire extinguishing agents to dangerous and hard-to-reach fire zones. Their use makes it possible to reduce the impact of dangerous fire factors on rescuers. The use of UAVs is especially relevant when extinguishing fires in high-rise buildings, industrial facilities, warehouses and wooded areas. Extinguishing such fires is accompanied by: high temperature, significant smoke, the presence of toxic combustion products and the threat of structural collapse [1].

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At the same time, the practical use of UAVs directly for extinguishing fires is associated with a number of technical limitations. These include limited payload and flight duration, the influence of wind loads, as well as a decrease in positioning accuracy in smoke and turbulence conditions. A separate technical task is to ensure a stable position of the UAV during the supply of fire extinguishing agents. In the process of water flowing out of the fire hose, a reactive force arises, directed opposite to the direction of the jet flow. In ground-based fire extinguishing systems, the effect of this force is compensated by the rescuer, the mass of the equipment or the supporting structure, while for the UAV it is an external destabilizing factor [2].

When supplying fire extinguishing agents through a fire hose installed on the UAV, reactive forces can cause a change in the spatial position of the device, violate its angular stability and create additional moments that must be compensated for by the stabilization system. Therefore, the magnitude of the reactive force of the water jet must be taken into account when determining the design and operational parameters of the UAV intended for fire extinguishing.

In the case of supplying fire extinguishing agents through a suspended hose line, the load on the UAV is determined not only by the reactive force of the jet. The device is also affected by the hose tension force, caused by the mass of the water column, hydrodynamic processes that occur during its filling and subsequent supply of fire extinguishing agents. Therefore, the ratio of these components may vary depending on the supply pressure and the altitude of the UAV location. Therefore, determining only the reactive force on the fire hose is insufficient to assess the full force load on the UAV.

In this regard, it is necessary to study the force interaction between the water jet, fire hose, suspended hose line and UAV. The results obtained can be used to select the design and operational parameters of the UAV, select the permissible modes of supply of fire extinguishing agents, as well as develop effective stabilization systems during fire extinguishing.

Therefore, study of the patterns of force loads on UAVs during the delivery of fire extinguishing agents through a fire hose is relevant. This can create a basis for a well-founded choice of UAV parameters and increase their stability during fire extinguishing.

2. Literature review and problem statement

Modern study in the field of UAV applications covers a wide range of issues related to improving their design, control systems, autonomous navigation, performing specialized tasks, and ensuring stability under the influence of external disturbances. In the case of using UAVs for firefighting, these tasks are supplemented by the delivery of fire extinguishing agents and substances, their directed delivery to the fire center, and ensuring the stable position of the device during such operations. Of particular importance are the force loads that arise during the delivery of fire extinguishing agents through the fire barrel and are transmitted to the UAV. They can affect the stability of the device, the accuracy of jet guidance, the operation of the stabilization system, and the design parameters of fire equipment mounting nodes. The paper [3] systematizes modern directions in the development of UAVs, in particular the issues of their classification, design, autonomy, the use of artificial intelligence, group interaction, and cooperative control. The issue of UAV control is discussed in more detail in [4], where classical, nonlinear and intelligent control algorithms are analyzed, taking into account the nonlinearity of the vehicle dynamics, parametric uncertainties and external disturbances. The results of these studies characterize the main trends in the development of UAVs and approaches to ensuring their stability and autonomy. At the same time, the force loads that arise during the supply of fire extinguishing agent through the fire hose and are transmitted to the aircraft are not directly investigated in [3, 4]. The possibilities of using UAVs directly during fire extinguishing are considered in [5, 6]. In [5], a UAV is proposed for extinguishing fires in dangerous and hard-to-reach areas by delivering and dropping fire extinguishing balls to the fire center. In [6], a quadcopter is developed to support fire extinguishing, capable of carrying spraying equipment with a hose. The authors pay the main attention to the design characteristics of the UAV, its load capacity, flight duration and the ability to perform certain firefighting operations. Thus, these studies confirm the practical possibility of using the UAV in conditions of limited access to the fire center, but do not provide a quantitative assessment of the complex force interaction between fire equipment, the flow of extinguishing agent, the hose line and the aircraft. The approach presented in [7], which considers a multirotor UAV connected to a flexible hose through which liquid is supplied under pressure to a nozzle installed on the aircraft, is closest to the problem under study. The authors investigate the interaction of the liquid flow with the flexible hose and the UAV and take into account the forces caused by it as external disturbances in the dynamic model of the aircraft. The reactive action of the jet on the nozzle is considered separately, and to ensure stability during the liquid supply, its active compensation by the control system is proposed. The results of physical experiments confirm the influence of hydrodynamic disturbances on the position of the UAV and the need to take them into account in the stabilization system. At the same time, the study [7] is not aimed at a systematic experimental determination of the forces acting directly on the fire hose and the suspended hose line, while varying the pressure, nozzle diameter and UAV altitude.

Important for the analysis of force loads are works [8, 9], which investigated the reaction of the fire hose and the force interaction in the system "hose-nozzle-water jet". In work [8], based on the law of conservation of momentum, the reaction of the nozzle and the tension of the fire hose were analyzed. It was shown that the reaction of the nozzle is determined by the jet pulse flow, and for its calculation, parameters characterizing the diameters of the hose and jet, water flow rate and static pressure in front of the nozzle can be used. At the same time, the model adopted in this work is based on the assumption of a flexible hose in contact with a horizontal surface, which differs from the operating conditions of a suspended UAV hose line.

An experimental study of the recoil force of a fire hose line was performed in work [9]. The authors showed that the load perceived by the operator when working with the hose line is determined not only by the reaction of the nozzle, but also by the configuration of the hose and the method of its holding. In particular, the magnitude of the recoil force varied depending on the spatial position of the hose line. This result is important for the study of UAVs, since in this case the hose is in a suspended state, and its spatial configuration and the mass of the water-filled area create an additional load on the aircraft.

The hydraulic characteristics of fire hoses were investigated in [10]. According to the results of experimental tests, the characteristics of pressure losses for fire hoses of different diameters were determined and the dependence of these losses on the parameters of the hose line and the flow regime was

established. Pressure losses determine the hydraulic conditions of water supply and, depending on the specified system parameters, affect the pressure before the nozzle, the flow rate and the speed of the jet outflow. Accordingly, these characteristics must be taken into account when analyzing the reactive load of the fire hose. At the same time, in [10] traditional fire hose lines were investigated without taking into account their vertical suspension at a considerable altitude and the load that such a hose line creates on the UAV.

A separate direction of the study is presented by works [11, 12], which consider flying water-jet fire extinguishing systems. The fundamental feature of such systems is the use of water flow not only for extinguishing a fire, but also for creating controlled forces and moments that ensure the movement and stabilization of the system. The works investigate the dynamics of such systems and approaches to controlling their spatial position by changing the parameters of water-jet drives. The results obtained indicate a direct connection between the characteristics of water jets and the dynamics of the system's movement. At the same time, the design principle of water-jet systems [11, 12] is significantly different from a multirotor UAV with a suspended hose line. In water-jet systems, the reactive forces of the jets are used as a control influence. For a multirotor UAV, the reactive force that occurs during the supply of fire extinguishing agent through the fire barrel is an external force load that must be taken into account and compensated for.

A similar principle is used in flying robots of the hose type, studied in works [13, 14]. Their design involves the creation of controlled reactive forces using water jets, which ensures the lifting, spatial movement and stabilization of the robot. In work [13], the possibility of stable maintenance of a hose robot in the air by controlling the direction of the resulting reactive force was experimentally demonstrated. This was further presented in work [14], where a system with several water nozzles designed to generate forces and moments necessary for controlling the robot and performing fire extinguishing operations was studied. At the same time, such systems are structurally different from a multirotor UAV, since the hose is the main element of the robotic system, and the reactive forces of water jets are purposefully used to ensure its movement. For a multirotor UAV that holds a fire hose and a suspended hose line, the corresponding force loads, on the contrary, must be compensated by a traction system and a stabilization system.

The issue of physical interaction of UAVs with the environment is summarized in the work [15], devoted to aerial manipulation using multirotor platforms. It is shown that the possibility of creating and compensating forces during such interaction depends on the configuration of the aircraft, the placement of additional equipment and the available directions of formation of control forces. This justifies the need to take into account external force loads when choosing the structural and traction scheme of the UAV, as well as the parameters of its control system. At the same time, the work [15] is of a survey nature and covers mainly the mechanical contact interaction of the UAV with objects, without separately considering the reactive action of the water jet and the load from the suspended fire hose line.

Close to the problem under study in terms of the nature of the force interaction are the works [16, 17], devoted to the use of UAVs for washing surfaces with high-pressure water. In [16], a multirotor aerial robot Flying Washer was developed, in which the reactive force arising during the outflow of water from the high-pressure nozzle is considered as an external load on the aircraft. To compensate for it, an additional traction system was used, which allows counteracting the reactive force without significantly changing the spatial position of the multirotor platform. Experimental results confirmed the possibility of compensating for such a load during water supply. In [17], a UAV equipped with a water supply system through a high-pressure hose was considered, and the reactive forces and moments arising during the operation of such a system were analyzed. The main attention was paid to modeling the force interaction of the "UAV-hose-jet" system and ways to reduce the impact of these loads on the aircraft. Studies [16, 17] confirm the need to take into account reactive forces and moments when designing multirotor systems that supply liquid under pressure. However, these works are primarily focused on the technological cleaning of surfaces and involve fluid supply modes, nozzle designs, and operating conditions that are different from those typical for firefighting.

In [18], a three-dimensional hybrid kinematic-force model is proposed for estimating the force of a liquid jet created by an aerial robot during high-pressure water delivery. The model combines a kinematic description of the system with an estimation of the jet force at the point of its interaction with the surface and allows taking into account the spatial position of the nozzle, the distance to the target surface, and the flow parameters. The proposed approach was verified by the results of modeling and experimental studies using physical prototypes. At the same time, work [18] is focused on estimating and controlling the jet force at the point of its contact with the surface and does not provide for a comprehensive determination of force loads in the "UAV – suspended hose line – fire hose" system, which is typical for firefighting tasks.

Analysis of works [3–18] shows that in the scientific literature, individual components of the problem under consideration have been studied. In particular, the designs and control systems of UAVs have been considered, as well as the use of unmanned platforms for firefighting. Separate studies have been devoted to the interaction of aircraft with flexible hoses, the reaction of fire nozzles, the recoil force of hose lines and hydraulic losses in fire hoses. Methods of compensating external forces and moments in liquid-coupled air systems have also been studied. At the same time, the force loads in the configuration of a multirotor UAV for firefighting with a suspended hose line remain insufficiently studied. In such a system, the aircraft is simultaneously affected by the reactive force of the jet and the load caused by the mass and spatial position of the water-filled hose line.

In particular, it requires experimental establishment of the influence of the altitude of the UAV lift, the pressure in front of the fire hose, the diameter of the nozzle and the duration of the supply of the extinguishing agent on the power parameters of the system. This justifies conducting full-scale tests at altitudes of 30–50 m with simultaneous determination of the forces in the fire hose mounting nodes, the jet reactive force and the tension force of the suspension system with subsequent mathematical generalization of the results obtained. The established dependencies can be used as initial data for substantiating the design parameters of the UAV, the selection of permissible modes of supply of extinguishing agents and the determination of requirements for the stabilization system when designing a UAV for fire extinguishing. All this allows to state that it is advisable to conduct a study devoted to the experimental determination of the regularities of the formation of power loads on the UAV during the supply of extinguishing agents. Particular attention requires establishing the regularities of the influence of the altitude of the UAV lift,

the pressure in front of the fire hose, and the diameter of the nozzle. It is necessary to simultaneously determine the forces in the fire hose attachment points, the jet reactive force and the tension force of the suspension system. The obtained patterns can be used to substantiate the design parameters of the UAV, the permissible modes of supplying fire extinguishing agents and the requirements for the stabilization system.

3. The aim and objectives of the study

The aim of the study is to determine the patterns of the formation of force loads on the UAV depending on the altitude, pressure, nozzle diameter. This will allow to substantiate the design parameters of the UAV, the permissible modes of supplying fire extinguishing agents and the requirements for their stabilization systems during fire extinguishing.

To achieve the set aim, it is necessary to solve the following objectives:

– to develop an experimental unit for studying the force loads that arise during the supply of fire extinguishing agents through the fire hose, with imitation of its retention by the UAV;

– to conduct experimental studies of the reactive forces that arise during the supply of fire extinguishing agents through the fire hose at altitudes of 30–50 m;

– to build regression models of forces F_1–F_5 based on a full factorial experiment;

– to build a quadratic regression model of the tension force of the suspension system F6 depending on the time of water supply and the lifting altitude;

– to analyze the response surfaces of forces F_1–F_6, to establish the features of the influence of the studied factors on the formation of force loads and to determine the limits of application of the obtained regression models.

4. Materials and methods

4. 1. The object and hypothesis of the study

The object of the study is the process of forming force loads during the supply of fire extinguishing agents through a fire hose held by a UAV. The scientific hypothesis is based on the assumption that the resulting force load on the UAV during the supply of fire extinguishing agents is formed as a complex non-additive effect of the dynamic reactive force of the jet and the tension of the suspended hose line and requires experimental study.

In the process of the study, it was assumed that the experimental unit reproduces the main force interactions characteristic of holding the fire hose of the UAV.

A simplification was adopted, according to which the force loads were studied without taking into account the dynamic reaction of the UAV and the operation of the stabilization system.

4. 2. Experimental unit and measuring force parameters

Full-scale studies were performed on a developed experimental unit designed to study the reactive forces that arise during the supply of fire extinguishing agents through a fire hose. A detailed description of this unit is given in section 5. 1.

4. 3. Plan of the field experiment

Table 1 shows the conditions for conducting the field experiment.

Table 1

Conditions of the field experiment

Parameter	Values
Lifting altitude h, m	30; 40; 50
Pressure in front of the barrel p, bar	4; 6; 8
Nozzle diameter d, mm	5; 6; 7
Number of repetitions	3 for each combination
Number of full-scale experiments in the work	81

For each altitude value, nine combinations of pressure in front of the barrel and nozzle diameter were investigated. Each combination of experimental parameters was repeated three times. Thus, 27 experiments were performed at each altitude, and the total number of field experiments for altitudes of 30, 40 and 50 m was 81.

4. 4. Experimental data processing

During each experiment, the force values from each dynamometer were recorded every 2 s for 30 s of water supply. The values at time $t = 0$ were not taken into account, therefore, for each force parameter, 15 values were obtained at time points 2, 4, 6, …, 30 s. Since six force parameters F_1–F_6 were determined simultaneously, 90 values were obtained within one experiment. In total, 81 field experiments were performed, therefore, the formed array of experimental data contained 7290 values of force parameters. All force values were recorded in newtons (N).

During the processing of experimental data, the change in power parameters was analyzed during 30 s of water supply. The largest values of loads were determined separately and the nature of their change in time was assessed.

For further regression analysis, three characteristic time points were selected – 4, 14 and 24 s from the start of water supply. The values obtained at the 4^{th} second characterized the initial stage of load formation and transfer, at the 14^{th} second – the transitional mode, and at the 24^{th} second – the stabilized mode. The choice of the moment of 24 s was based on the analysis of the time dependences of power parameters, according to which by this time their change became insignificant and the mode acquired a stable nature. Data recorded in the interval 26–30 s were used to confirm the preservation of the stabilized load mode.

4. 5. Regression modeling method

Taking into account the physical nature of the studied loads, the factors shown in Fig. 1. During the test, the pressure in front of the barrel, the nozzle diameter, the water supply time, and the lifting altitude were changed. The flow rate and jet velocity were considered as derived hydraulic parameters.

The consumption of fire extinguishing agents and the jet speed directly affect the magnitude of power loads, however, in the full factorial design they were not considered as independent variables, since they depend on the pressure in front of the fire hose and the diameter of the nozzle. Other parameters that can affect the studied power characteristics during the tests were not varied and were not included in the factorial design.

To determine the dependence of forces F_1–F_5, a full factorial design was used for three factors, namely the time of fire extinguishing agent supply t, the pressure in front of the fire hose p and the diameter of the nozzle d. The lower and

upper levels of the factors were $t = 4$ and 24 s, $p = 4$ and 8 bar, $d = 5$ and 7 mm, which are given in Table 2. The values $t = 14$ s, $p = 6$ bar and $d = 6$ mm corresponded to the center of the factor space and to describe the intermediate regimes. When constructing mathematical dependencies, the main effects of the factors, their pair interactions and triple interaction were taken into account.

To analyze the tension force of the F_6 suspension system, the time of fire extinguishing agent supply t and the lifting altitude h were considered as independent factors. Three levels of each factor were used: altitudes $h = 30$, 40 and 50 m and three time levels $t = 4$, 14 and 24 s.

The obtained data were used to establish the dependence of the F_6 force on the time of fire extinguishing agent supply and lifting altitude.

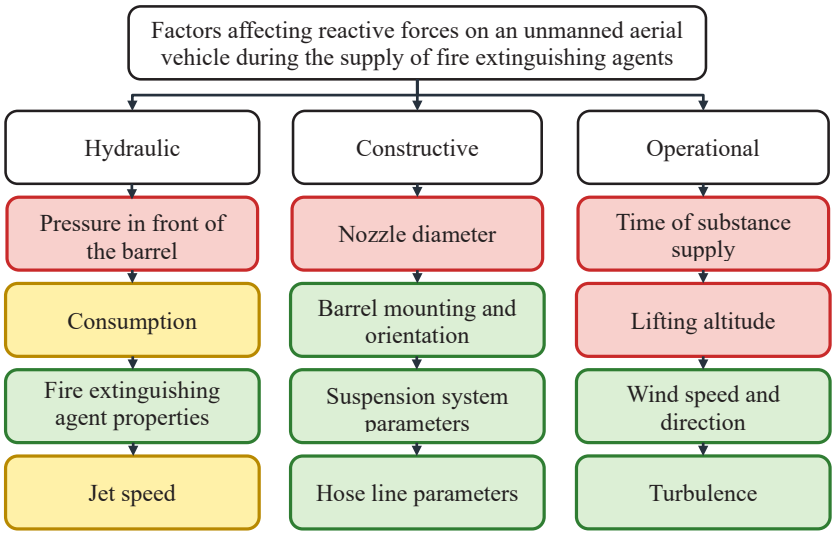


Fig. 1. Factors influencing power loads during water supply from unmanned aerial vehicles

Given the possible nonlinearity of the dependencies and the need to take into account the interactions of factors, the general form of the regression model is given by the equality

$$F = \sigma_0 + \sigma_1 x_1 + \sigma_2 x_2 + \sigma_3 x_3 + \sigma_4 x_1 x_2 + \\ + \sigma_5 x_1 x_3 + \sigma_6 x_2 x_3 + \sigma_7 x_1 x_2 x_3, \quad (1)$$

where F – the modeled force, N; σ_0, σ_1, σ_2, σ_3, σ_4, σ_5, σ_6, σ_7 – regression coefficients; x_1, x_2, x_3 – coded values of the factors given in Table 2.

To estimate the coefficients of model (1), eight combinations of extreme levels of factors were used, corresponding to the full factorial design given in Table 3.

The given Table 3 covers all possible combinations of the lower and upper levels of the three studied factors. Such a plan allows to estimate the separate influence of each factor and to determine the effects of their interaction.

Table 2

Factor levels in the full factorial experiment

Factor	Lowest value (–)	Average value (0)	Highest value (+)
Time, t, s	4	14	24
Pressure, p, bar	4	6	8
Nozzle diameter, d, mm	5	6	7

Table 3

Matrix of planning a full factorial experiment

Experiment No.	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$
1	+	+	+	+	+	+	+
2	–	+	+	–	–	+	–
3	+	–	+	–	+	–	–
4	–	–	+	+	–	–	+
5	+	+	–	+	–	–	–
6	–	+	–	–	+	–	+
7	+	–	–	–	–	+	+
8	–	–	–	+	+	+	–

The applied approach creates the basis for the mathematical description of the forces F_1–F_5 depending on the regime parameters of the supply of fire extinguishing agents through the fire hose.

5. Results of determining the patterns of the influence of force loads on an unmanned aerial vehicle

5. 1. Results of the development of an experimental unit for studying force loads during the supply of fire extinguishing agents through the fire hose

The field studies were carried out on the developed experimental unit designed to study the reactive forces that arise during the supply of fire extinguishing agents through the fire hose (Fig. 2).

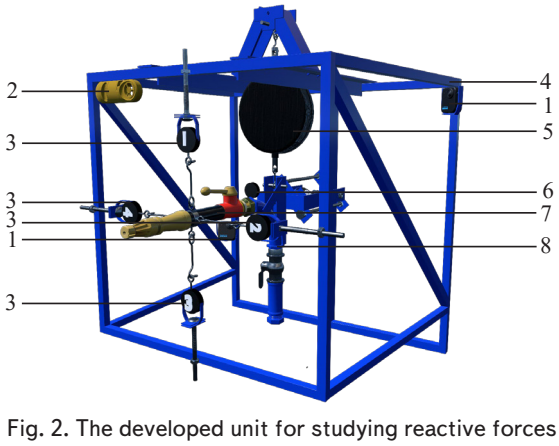


Fig. 2. The developed unit for studying reactive forces on fire barrels: 1 – GoPro HERO 11 BLACK mini camera; 2 – Kestrel 4000 Pocket Weather Meter weather station; 3 – VP-10 dynamometer; 4 – frame; 5 – DPU-5-2 5033 UHL4.2 dynamometer; 6 – Aquatica pressure gauge; 7 – MSB-1915 fire barrel (with a nozzle of 5.6 and 7 mm); 8 – knee

The unit included a supporting frame, a fire hose fastening system, measuring instruments, hydraulic elements and video recording equipment. Dynamometers VP-10 (China) and DPU-5-2 5033 UHL4.2 (Ukraine) were used to record forces; a fire hose MSB-1915 with interchangeable nozzles

with a diameter of 5, 6 and 7 mm was used as a working element. The pressure in front of the hose was controlled by an Aquatica manometer, (China) the course of the experiment and the dynamometer readings were recorded using a GoPro HERO 11 Black Mini camera (USA) the external environment parameters were monitored by a Kestrel 4000 Pocket Weather Meter weather station. (USA)

The supply of fire extinguishing agents was carried out using the pumping equipment of a MERCEDES-BENZ Atego 1428F fire tanker (Germany) through hose lines with a diameter of 77 and 25 mm.

The lifting altitude of the experimental installation was provided by a cranked lift AD-53 (MB ACTROS 6×4) (Germany).

To determine the nature of the force loads that arise during the supply of water through the fire hydrant, a scheme for applying and measuring forces was developed, shown in Fig. 3. The scheme reflects the directions of action of forces in the fire hydrant fastening nodes, the jet reactive force and the load on the suspension system.

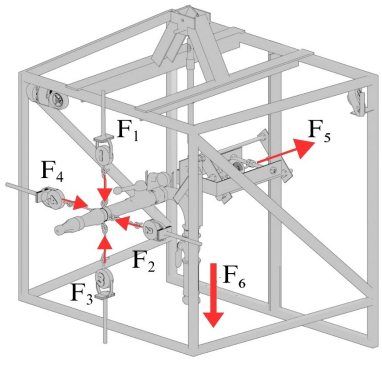


Fig. 3. Scheme of applying forces to the elements of the experimental installation: F_1–F_4 – forces in the fire hydrant fastening elements, F_5 – jet reactive force, F_6 – tension force of the suspension system

Forces F_1–F_4 characterized the forces in the upper, left, lower and right fire hydrant fastening elements, respectively. F_5 was defined as the main jet reactive force. F_6 characterized the tension of the suspension system, which is formed due to the mass of the filled hose line, water column and hydrodynamic load.

Full-scale experiments were carried out with the lifting of the experimental installation to specified altitudes using a cranked lift. The general view of conducting experimental studies with water supply through the fire hydrant is shown in Fig. 4.



Fig. 4. Conducting full-scale experimental studies of reactive forces during water supply through a fire hydrant using a cranked lift

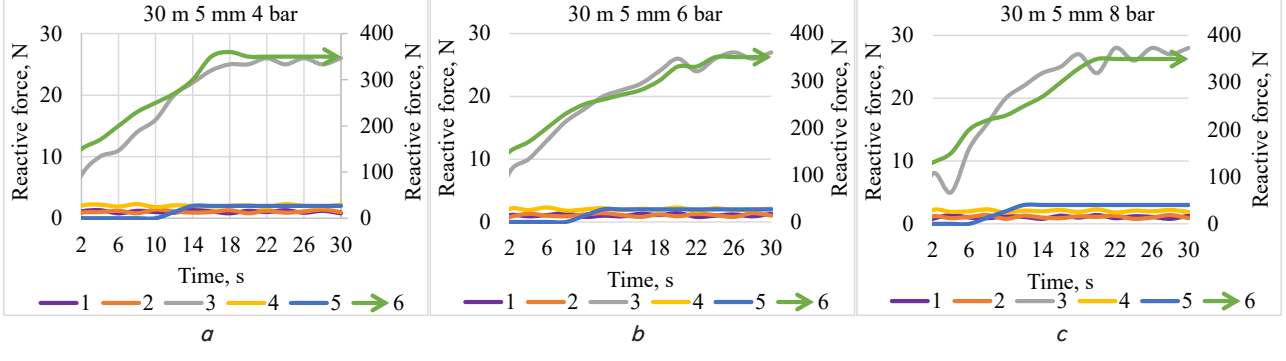
5. 2. Results of experimental studies of reactive forces arising during the supply of fire extinguishing agents through a fire hydrant

The analysis of the experimental results showed that with increasing lifting altitude, the tension force of the suspension system F_6 increases first of all, while the magnitude of the jet reactive force F_5 is largely determined by the pressure in front of the fire hydrant and the diameter of the nozzle. For all studied altitudes, the nature of the change in force parameters was similar, but their absolute values increased with increasing altitude.

At an altitude of 30 m after stabilization of the fire extinguishing agent supply mode, the tension force of the suspension system was approximately 340–350 N. The lower dynamometer in most of the studied modes recorded a value of 24–28 N, which characterizes the distribution of mechanical load in the corresponding fastening node of the fire hydrant. The test results for nozzles with a diameter of 5, 6 and 7 mm are shown in Fig. 5–7.

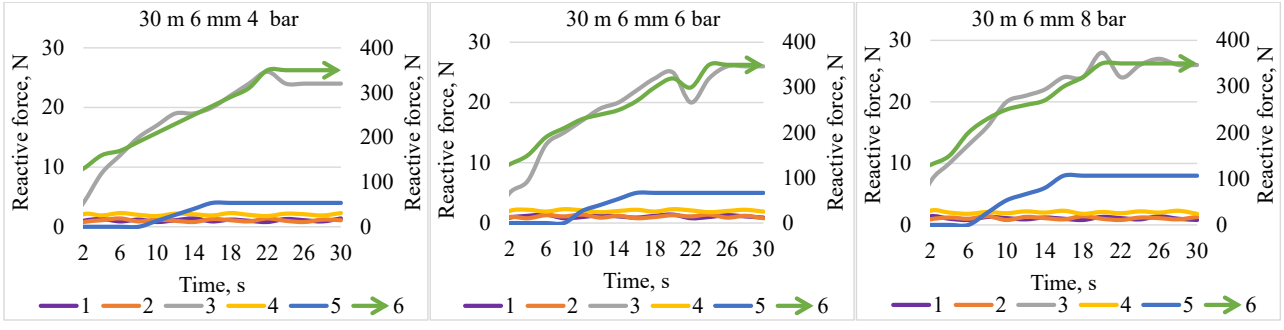
When using a nozzle with a diameter of 5 mm, the reactive force F_5 at an altitude of 30 m remained relatively small compared to the tension force of the suspension system.

With an increase in the nozzle diameter to 6 mm, the values of the reactive force F_5 increased, however, the main component of the force load remained the tension force of the suspended hose line filled with water.



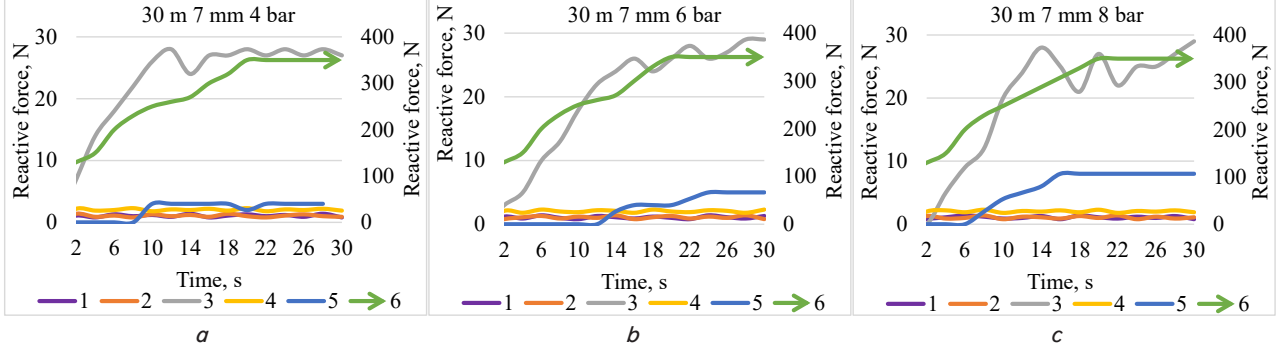
a *b* *c*

Fig. 5. Results of experimental studies of reactive forces at an altitude of 30 m with a nozzle diameter of 5 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



a *b* *c*

Fig. 6. Results of experimental studies of reactive forces at an altitude of 30 m with a nozzle diameter of 6 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



a *b* *c*

Fig. 7. Results of experimental studies of reactive forces at an altitude of 30 m with a nozzle diameter of 7 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar

With a nozzle diameter of 7 mm, the largest values of the reactive force F_5 among the three studied diameters were recorded. This trend is consistent with the change in the hydraulic parameters of the jet due to an increase in the area of the outlet cross-section of the nozzle.

At an altitude of 40 m, the general nature of the change in the force parameters was preserved, but the absolute values of the loads increased. The tension force of the suspension system was approximately 366–390 N, which is associated with an increase in the length of the suspended and water-filled hose line. The results of experimental studies for this altitude are shown in Fig. 8–10.

For a nozzle with a diameter of 5 mm, the reactive force F_5 varied approximately within the range of 22–33 N.

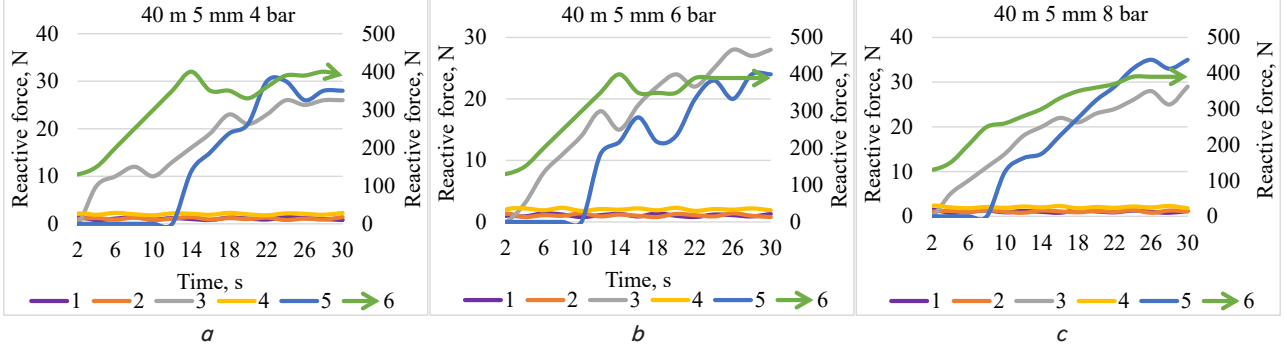
Using a nozzle with a diameter of 6 mm, the reactive force F_5 increased to 42–43 N, and for a nozzle with a diameter of 7 mm it reached approximately 44–45 N.

Therefore, with an increase in the nozzle diameter, the reactive load on the fire hose increased, but the tension force of the suspension system remained the largest component of the total force load.

The largest values of force loads in the studied altitude range were recorded at a height of 50 m. This mode is characterized by a combination of the largest length of the suspended hose line filled with water and increased values of the jet reactive force. The tension force of the suspension system was approximately 396–428 N, which is the largest range of values among the studied altitudes. The results of experimental studies for an altitude of 50 m are shown in Fig. 11–13.

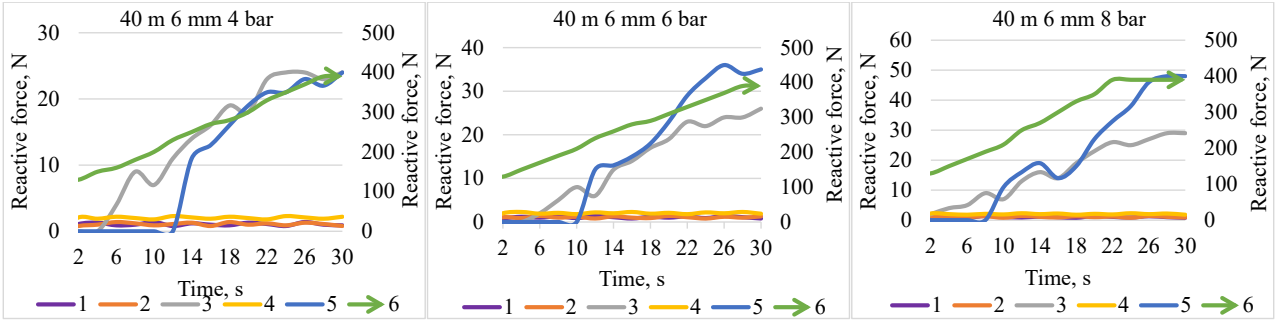
When using a nozzle with a diameter of 5 mm, the reactive force F_5 at an altitude of 50 m was approximately 34–49 N.

For a nozzle with a diameter of 6 mm, the reactive force reached about 54 N, and for a nozzle with a diameter of 7 mm it exceeded 54 N. The highest load values were observed at a pressure of 8 bar and the use of nozzles with a diameter of 6–7 mm. Under these conditions, the highest tension force of the suspension system and an increased reactive load from the jet were simultaneously recorded.



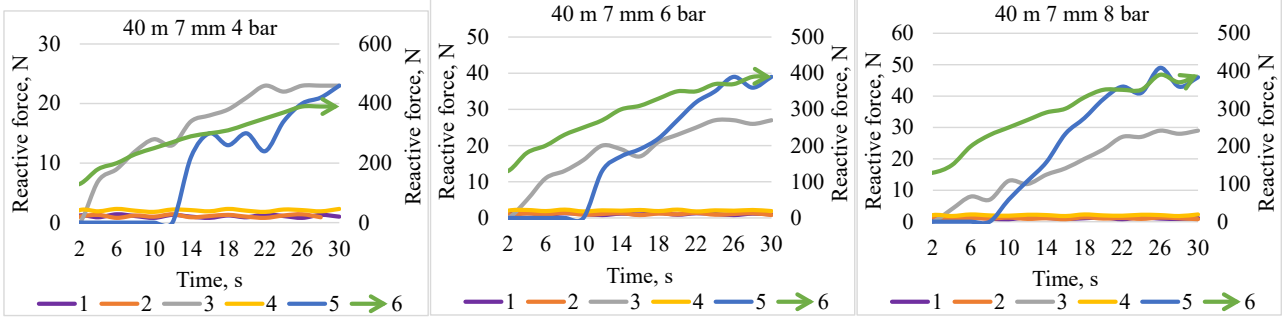
a *b* *c*

Fig. 8. Results of experimental studies of reactive forces at an altitude of 40 m with a nozzle diameter of 5 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



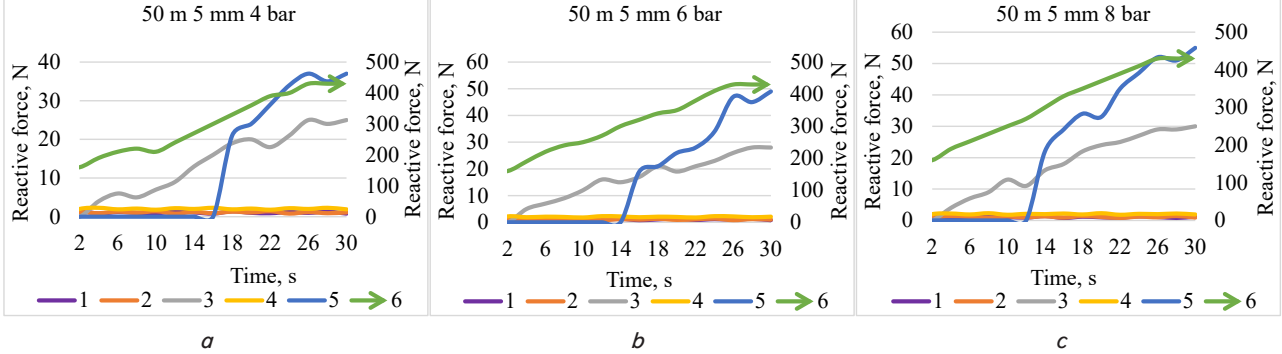
a *b* *c*

Fig. 9. Results of experimental studies of reactive forces at an altitude of 40 m with a nozzle diameter of 6 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



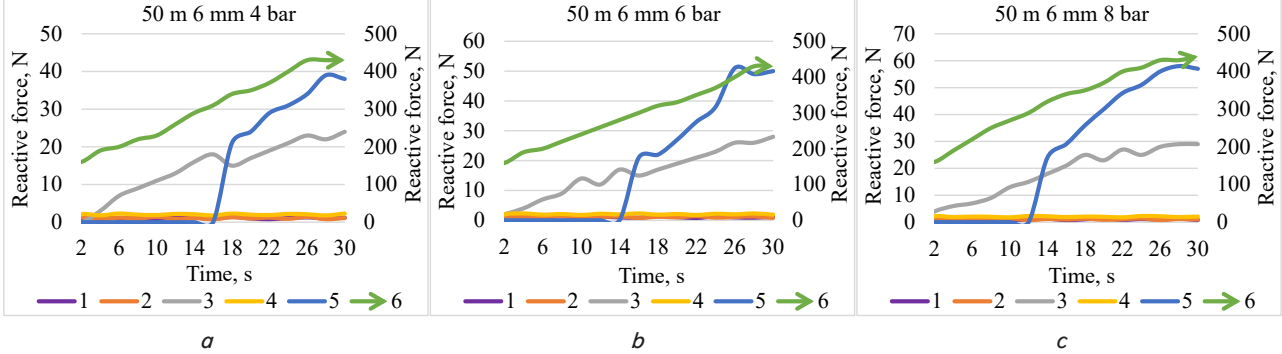
a *b* *c*

Fig. 10. Results of experimental studies of reactive forces at an altitude of 40 m with a nozzle diameter of 7 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



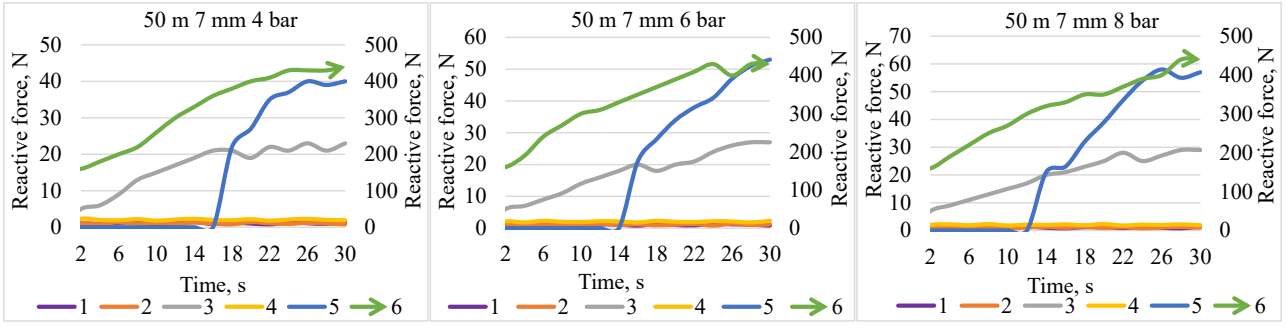
a *b* *c*

Fig. 11. Results of experimental studies of reactive forces at an altitude of 50 m with a nozzle diameter of 5 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



a *b* *c*

Fig. 12. Results of experimental studies of reactive forces at an altitude of 50 m with a nozzle diameter of 6 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar



a *b* *c*

Fig. 13. Results of experimental studies of reactive forces at an altitude of 50 m with a nozzle diameter of 7 mm: *a* – 4 bar; *b* – 6 bar; *c* – 8 bar

Comparison of the results for the three studied altitudes showed a consistent increase in the tension force of the suspension system F_6: approximately 340–350 N at an altitude of 30 m, 366–390 N at an altitude of 40 m and 396–428 N at an altitude of 50 m. Therefore, within the studied range of 30–50 m, the increase in altitude was accompanied by an increase in the load, associated primarily with an increase in the length of the suspended hose line and the mass of water contained in it.

In general, the relative errors of the investigated reactive forces for all series of experimental studies were within 11–19%, which is acceptable for this type of the study.

Comparison of the limits of the established ranges of F_6 showed that with an increase in altitude from 30 to 40 m, the corresponding values increased by approximately 7.6–11.4%, and from 30 to 50 m – by 16.5–22.3%. Such ratios characterize the general tendency of the load increase with altitude, but do not indicate the presence of a strictly proportional dependence, since the value of F_6 is formed under the combined influence of geometric, hydraulic and design factors

The reactive force of the jet F_5 had smaller absolute values compared to the tension force F_6, but its value increased with increasing pressure in front of the fire hose and nozzle diameter. This indicates the need to take into account the reactive force not only when assessing the loads on the fire hose, but also when determining the requirements for the UAV stabilization system.

The total force load on the system under study is formed as a result of the simultaneous action of components of different physical nature. A significant part of it is the tension force of the suspension system, associated with the mass of the hose line, the water contained in it, and the installed equipment. An additional load is created by the reactive force of the jet, the magnitude of which is determined by the parameters of the fire extinguishing agent supply and the geometric characteristics of the nozzle.

The forces F_5 and F_6 cannot be directly arithmetically summed up without taking into account the directions of their action, the points of application and the geometry of the fire hose attachment. For a specific UAV design, the resulting force load and the moments created by it must be determined in accordance with the spatial calculation scheme of the system.

The obtained experimental data also do not provide grounds to describe the influence of altitude on the force F_6 by a simple directly proportional dependence. The nature of its change is determined not only by the altitude of the lift, but also by the development of the processes of filling and stabilizing the hose line in time. Similarly, the forces F_1–F_5 are formed under the joint influence of the time of fire extinguishing agent supply, the pressure in front of the fire hose and the diameter of the nozzle.

The practical significance of the obtained results lies in the possibility of using them as initial data for substantiating the traction reserve of the UAV, the parameters of the fire hose mounting nodes and the requirements for the stabilization system when operating at altitudes of 30–50 m. In this case, it is necessary to simultaneously take into account the load from the suspended hose line and the reactive action of the jet, since these components have a different physical nature, different directions of action and can affect the spatial stability of the aircraft in different ways.

To quantitatively describe the joint influence of the studied parameters, the results of full-scale tests were subsequently used to construct regression relationships. For the forces F_1–F_5, the influence of the time of fire extinguishing agent supply, the pressure in front of the fire hose and the diameter of the nozzle was assessed. The tension force of the F_6 suspension system, the formation of which has a different physical nature, was described separately depending on the time of supply of the extinguishing agent and the altitude of the lift.

5. 3. Regression models of averaged forces F_1–F_5 in the altitude range of 30–50 m

Based on the levels of factors given in Table 2 and the corresponding experimental design matrix in Table 3, the initial data for constructing models of forces F_1–F_5 were formed. Forces F_1–F_4 characterize the forces in the fire hydrant fastening nodes, and force F_5 is the reactive force of the jet.

For each of the forces F_1–F_5, the averaged values obtained from the test results at altitudes of 30, 40 and 50 m were used. This approach made it possible to describe the generalized response of the system within the studied altitude range without including altitude (h) in the composition of independent factors of the regression models. The initial values of the forces are grouped according to the experimental design matrix and are given in Table 4.

Table 4

Experimental values of forces F_1–F_5, N

Reactive force, N	1	2	3	4	5	6	7	8
F_1	1.23	1.1	1.27	1.0	1.17	1.17	1.3	0.8
F_2	0.8	1.07	1.07	0.9	1.13	1.07	0.87	1.0
F_3	25.3	6.33	24.67	10.0	23.67	5.67	24.0	10.0
F_4	2.1	2.1	2.17	2.03	2.23	1.97	2.27	2.03
F_5	21.7	0	14.33	0	20.67	0	22	0

The coefficients of the regression models F_1–F_5 were determined from the experimental data in Table 4, taking into account the orthogonality of the experimental design matrix. The obtained coefficient values are given in Table 5.

Table 5

Coefficients of the models F_1—F_5 in the coded variables

Coefficient	F_1	F_2	F_3	F_4	F_5
b_0	1.130	0.98875	16.2050	2.1125	9.8375
b_1	0.1125	−0.02125	8.2050	0.080	9.8375
b_2	0.0375	0.02875	−0.9625	−0.0125	0.7550
b_3	0.020	−0.02875	0.370	−0.0125	−0.830
b_{12}	−0.080	−0.03125	1.0375	−0.0150	0.7550
b_{13}	−0.0125	−0.00375	0.2050	−0.0450	−0.830
b_{23}	−0.0225	−0.05375	0.2025	0.0125	1.0875
b_{123}	0.045	−0.07875	0.0375	−0.0200	1.0875

After substituting the coefficients from Table 5, the regression equation for the forces F_1–F_5 in the coded variables was obtained:

– force F_1 – force in the upper fixation element

$$F_1 = 1.130 + 0.1125x_1 + 0.0375x_2 + 0.020x_3 - 0.080x_1x_2 - 0.0125x_1x_3 - 0.0225x_2x_3 + 0.045x_1x_2x_3; \quad (2)$$

– force F_2 – force in the left fixing element

$$F_2 = 0.98875 - 0.02125x_1 + 0.02875x_2 - 0.02875x_3 - 0.03125x_1x_2 - 0.00375x_1x_3 - 0.05375x_2x_3 - 0.07875x_1x_2x_3; \quad (3)$$

– force F_3 – force in the lower fixing element

$$F_3 = 16.205 + 8.205x_1 - 0.9625x_2 + 0.370x_3 + 1.0375x_1x_2 - 0.205x_1x_3 - 0.2025x_2x_3 - 0.0375x_1x_2x_3; \quad (4)$$

– force F_4 – force in the right fixing element

$$F_4 = 2.1125 + 0.080x_1 + 0.0125x_2 + 0.0125x_3 - 0.015x_1x_2 - 0.045x_1x_3 + 0.0125x_2x_3 - 0.020x_1x_2x_3; \quad (5)$$

– force F_5 – jet reactive force

$$F_5 = 9.8375 + 9.8375x_1 + 0.755x_2 - 0.830x_3 + 0.755x_1x_2 - 0.830x_1x_3 + 1.0875x_2x_3 + 1.0875x_1x_2x_3. \quad (6)$$

After switching to natural variables, the regression equations take the form:

– force F_1 – force in the upper fixation element, N

$$F_1 = -1.240 + 0.12375t + 0.33125p + 0.294d - 0.0175tp - 0.01475td - 0.04275pd + 0.00225tpd; \quad (7)$$

– force F_2 – force in the left fixing element, N

$$F_2 = 1.959 - 0.13225t - 0.13325p - 0.193d + 0.0220625tp + 0.02325td + 0.02825pd - 0.0039375tpd; \quad (8)$$

– force F_3 – force in the lower fixing element, N

$$F_3 = 14.165 + 0.45375t - 1.6575p - 0.367d + 0.040625\text{tp} + 0.00925\text{td} + 0.075pd + 0.001875tpd; \quad (9)$$

– force F_4 – force in the right fixing element, N

$$F_4 = 2.401 + 0.0035t - 0.11725p - 0.071d + 0.00525tp + 0.0015td + 0.02025pd - 0.001tpd; \quad (10)$$

– force F_5 – jet reactive force, N

$$F_5 = -12.851 + 3.21275t + 1.154p + 1.637d - 0.2885tp - 0.40925td - 0.2175pd + 0.054375tpd. \quad (11)$$

Analysis of the obtained models shows that the nature of the influence of the studied factors differs significantly for individual components of the force load. For forces F_1, F_2 and F_4, the coefficients of the main effects and interfactor interactions have relatively small values. This indicates a limited change in these forces in the studied factor space. The most pronounced change was found for force F_3, which characterizes the load in the lower element of the fire hose fixation. The largest coefficient of the F_3 model was obtained for factor x_1. The value of this coefficient is 8.205 and significantly exceeds the coefficients for other main effects. The interaction of factors x_1 and x_2 also makes a noticeable contribution to the formation of F_3. For the jet reactive force F_5, the largest coefficient of the main effect also corresponds to factor x_1. The influence of factors x_2 and x_3 is smaller in absolute value. The presence of pair and triple interactions indicates that the influence of a separate factor on the force load depends on the levels of other factors.

The obtained regression relationships allow quantitatively describing the forces F_1–F_5 within the studied factor space. The constructed models can be used to estimate the force loads for given values of the water supply time, pressure in front of the barrel and nozzle diameter.

The application of the obtained relationships outside the studied factor intervals requires additional experimental verification.

5. 4. Regression model of the tension force F_6 depending on time and altitude

The tension force of the suspension system F_6 differs from the forces F_1–F_5 in the physical nature of its formation and the nature of the influence of the studied factors.

According to the results of field tests, it was established that its change is primarily associated with the time of the fire extinguishing agent supply and the altitude of the installation. Therefore, the force F_6 was not included in the common three-factor model F_1–F_5, but was described by a separate regression dependence on time t and altitude h.

For each combination of time t and altitude h, the arithmetic mean of nine values of force F_6 obtained for three pressure values $p = 4$, 6, 8 bar and three nozzle diameters $d = 5$, 6, 7 mm was determined

$$\bar{Y}(t,H) = 1/9 \sum F_6(t,h,p,d). \quad (12)$$

Table 6

Average values of the tension force of the suspension system F_6, N

Altitude h, m	t = 4 s	t = 14 s	t = 24 s
30	151.11	271.11	350.00
40	190.00	306.67	387.78
50	194.45	313.33	412.22

To build a regression model, three levels of fire extinguishing agent application time were used – 4, 14 and 24 s and three levels of altitude – 30, 40 and 50 m. For further calculations, the coded values were matched with this equation:

$$X_2 = \frac{(t-14)}{10}, \quad (13)$$

$$X_2 = \frac{(h-40)}{10}. \quad (14)$$

Respectively: t = 4, 14, 24 s $\rightarrow x_1 = -1, 0, +1$; h = 30, 40, 50 m $\rightarrow x_2 = -1, 0, +1$.

Choosing the form of the regression model.

Since each of the studied factors is represented by three levels, a second-order polynomial model was adopted to approximate the experimental data, which takes into account linear and quadratic components, as well as pairwise interaction of factors

$$F_6 = b_0 + b_1x_1 + b_2x_2 + b_{12}x_1x_2 + b_{11}x_1^2 + b_{22}x_2^2. \quad (15)$$

The coefficients of the regression model were determined by the least squares method from the nine averaged experimental values of the tension force of the suspension system F_6, given in Table 6.

The obtained coefficients are given in Table 7.

Table 7

Coefficients of the F_6 model in coded variables

Coefficient	Value
b_0	305.55667
b_1	102.40667
b_2	24.63000
b_{12}	4.72000
b_{11}	–16.11000
b_{22}	–12.78000

Accordingly, the regression equation in the coded variables has the form

$$F_6 = 305.55667 + 102.40667x_1 + 24.630x_2 + \\ + 4.720x_1x_2 - 16.110x_1^2 - 12.780x_2^2. \quad (16)$$

The regression equation in the natural variables is given in the form

$$F_6 = -145.956267 + 12.863467t + \\ + 12.0262H + 0.0472tH - \\ - 0.1611t^2 - 0.1278H^2, \quad (17)$$

where F_6 – the tension force of the suspension system, N; t – time, s; h – the lifting altitude of the installation, m.

5. 5. Analysis of the response surfaces of forces F_1–F_6 and determination of the limits of application of regression models

Graphical analysis of the obtained regression dependencies is given in Fig. 14–19.

The response surfaces of the forces F_1–F_5 were constructed depending on the time of supply of the extinguishing agent and the pressure in front of the fire hose for fixed values of the nozzle diameter d = 5, 6 and 7 mm.

For the force F_6, the dependence on time t and altitude h was considered. The obtained graphical dependences were interpreted within the studied ranges of factors.

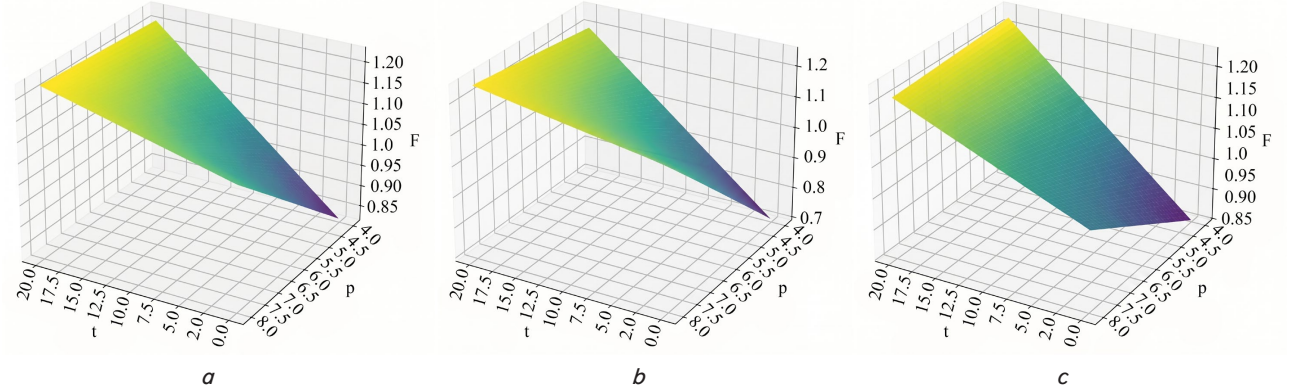
Fig. 14 shows the calculated surfaces of the force F_1 in the upper element of the fire hose fixation.

The graphical dependencies indicate a general trend of increasing the force F_1 with increasing the time of supplying the extinguishing agent. The influence of the pressure and diameter of the nozzle is manifested through a change in the slope and position of the surfaces, which is consistent with the presence of interfactor interactions in the regression model.

Fig. 15 shows the calculated surfaces of the force F_2 in the left fixing element of the fire hose.

The response surfaces for the force F_2 have different orientations depending on the diameter of the nozzle, which indicates the joint influence of time, pressure and geometric parameters on the magnitude of the force. At the same time, the calculated values vary in a relatively narrow range.

Fig. 16 shows the calculated surfaces of the force F_3 in the lower fixing element of the fire hose.



a *b* *c*

Fig. 14. Calculated surfaces of the force F_1 in the upper fixing element depending on the time t and pressure p: *a* – d = 5 mm; *b* – d = 6 mm; *c* – d = 7 mm

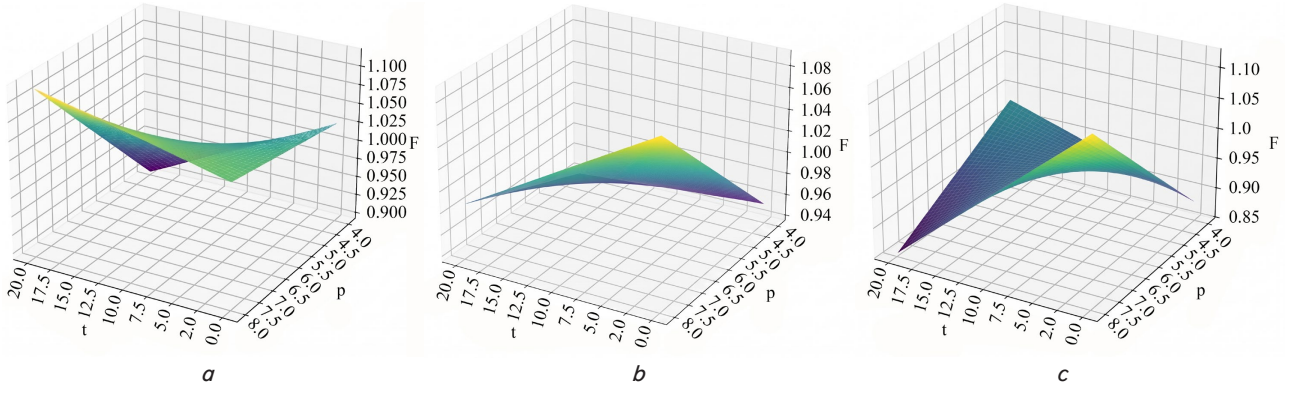


Fig. 15. Calculated surfaces of the force F_2 in the left fixing element depending on the time *t* and pressure *p*: *a* – *d* = 5 mm; *b* – *d* = 6 mm; *c* – *d* = 7 mm

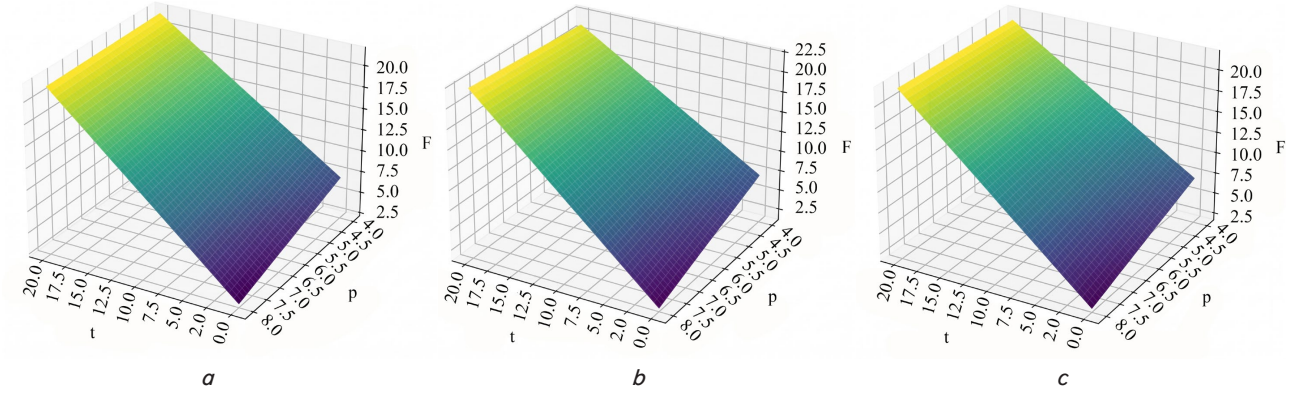


Fig. 16. Calculated force surfaces F_3 in the lower fixing element depending on time *t* and pressure *p*: *a* – *d* = 5 mm; *b* – *d* = 6 mm; *c* – *d* = 7 mm

All investigated diameters of the nozzle are characterized by a pronounced increase in the F_3 force with an increase in the time of supplying the extinguishing agent. The influence of pressure is less pronounced and depends on the combination of factor levels. Compared to forces F_1, F_2, and F_4, force F_3 is characterized by a wider range of changes, which indicates the significant role of the lower fixation element in load perception.

Fig. 17 shows the calculation surface of force F_4 in the right element of fixing the fire barrel. The surfaces are constructed in *t-p* coordinates separately for each of the investigated nozzle diameter values.

The response surfaces of F_4 are relatively flat, which indicates a limited change in the load in the studied factor space. The influence of time, pressure and nozzle diameter is manifested through their joint action, taken into account in the regression model.

Fig. 18 shows the calculated surfaces of the main reactive force F_5.

For all investigated nozzle diameters, a pronounced increase in the reactive force F_5 over time is observed. The pressure in front of the fire hose and the nozzle diameter affect the level of reactive load, and the nature of their action depends on the combination of the studied factors.

The obtained dependencies must be taken into account when justifying the permissible parameters of the supply of fire extinguishing agent.

Fig. 19 shows the calculated surface of the force F_6 depending on time and altitude.

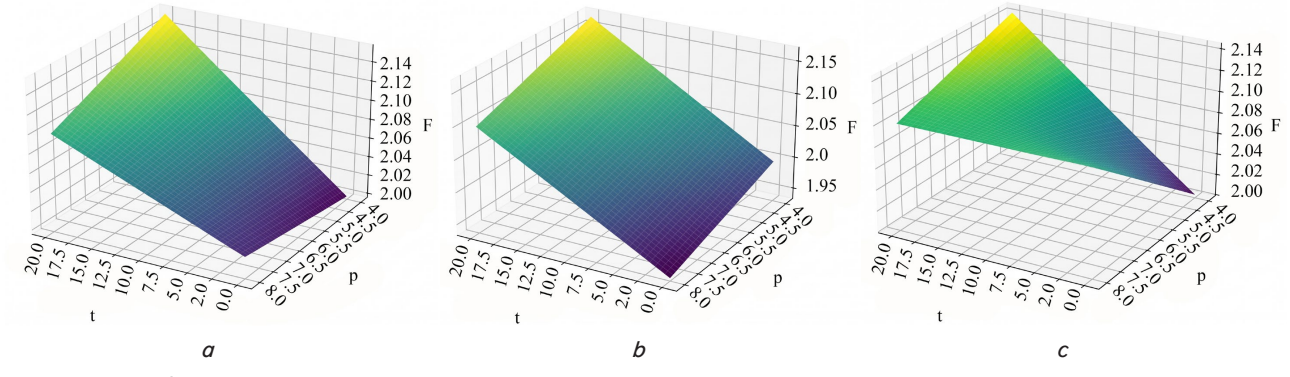


Fig. 17. Calculated surfaces of the force F_4 in the right fixation element depending on the time *t* and pressure *p*: *a* – *d* = 5 mm; *b* – *d* = 6 mm; *c* – *d* = 7 mm

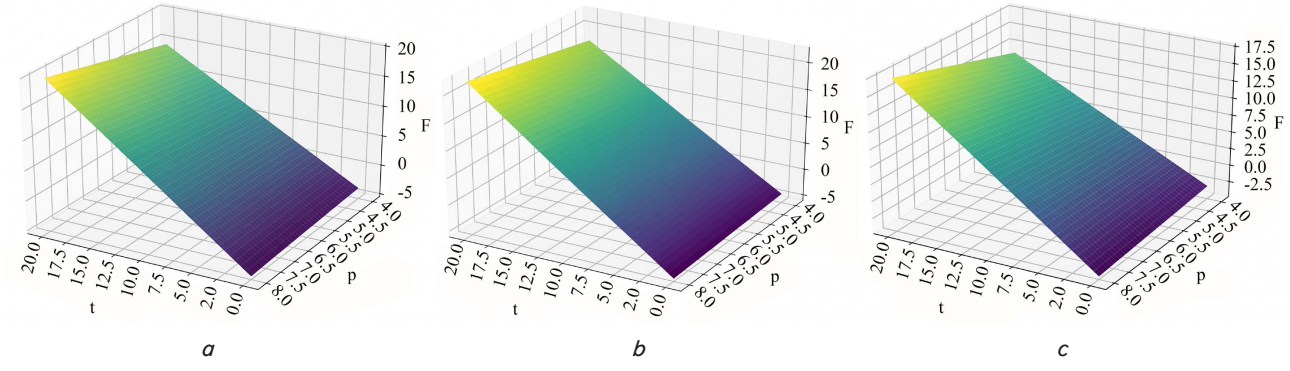


Fig. 18. Calculated surfaces of the reactive force F_5 depending on time t and pressure p: a – d = 5 mm; b – d = 6 mm; c – d = 7 mm

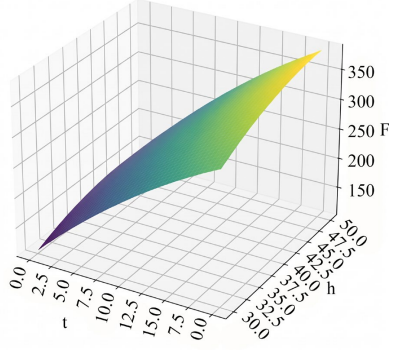


Fig. 19. The calculated surface of the tension force of the suspension system F_6 depending on the time t and the altitude h

The response surface F_6 is characterized by an increase in the tension force of the suspension system with an increase in the time of the fire extinguishing agent supply and the altitude of the lift. The most pronounced change is observed in the direction of the time axis, which is consistent with the processes of filling the hose line and forming a steady state. The influence of altitude is due to an increase in the length of the suspended hose line and the mass of water contained in it. The presence of quadratic components in the regression model reflects the nonlinear nature of the load change.

The obtained response surfaces indicate differences in the formation of individual components of the force load. The most pronounced change among the forces in the fastening nodes is the force F_3, while the forces F_5 and F_6 characterize, respectively, the reactive action of the jet and the tension of the suspension system. They must be taken into account when justifying the design parameters and permissible operating modes of UAVs for extinguishing fires.

The regression models of forces F_1–F_5 are saturated and accurately reproduce the experimental values in the nodes of the full factorial design. However, such correspondence is not an independent confirmation of their statistical adequacy. Therefore, it is advisable to limit the application of the obtained dependencies to the investigated factor intervals, and their predictive properties require additional experimental verification.

6. Discussion of the results of determining the patterns of the influence of force loads on an unmanned aerial vehicle

The obtained results show that the force loads during the supply of fire extinguishing agents through a fire hose are formed under the joint influence of several operational parameters. Within the studied modes, the patterns of force changes depending on the altitude, pressure in front of the fire hose and the diameter of the nozzle were established. The largest absolute values among the measured parameters were the tension force of the suspension system F_6. As can be seen from Fig. 5–13, its value naturally increased with increasing altitude. After stabilization of the mode, the force F_6 was 340–350 H at an altitude of 30 m and 366–390 N at an altitude of 40 m. At an altitude of 50 m, 396–428 N, which corresponds to the largest values in the studied altitude range. The increase in F_6 with increasing altitude is also confirmed by the average values given in Table 6, regression dependence (17) and response surface in Fig. 19. In particular, at t = 24 s the average value of F_6 increased from 350.00 H at an altitude of 30 m to 412.22 N at 50 m. Such a change can be explained by an increase in the length of the suspended hose line filled with water and a corresponding increase in the load on the suspended system. This is consistent with Fig. 19, where the most pronounced change in the design force is observed along the time axis. The quadratic regression model (17) reflects the joint influence of the feed time and the lifting altitude. The additional coefficient at the interaction term characterizes the joint action of these factors within the adopted regression model. The negative coefficients of the quadratic components determine the curvature of the surface and a decrease in the growth rate of the design force near the upper levels of the factors. Therefore, the nature of the change in F_6 cannot be described only by a simple proportional dependence on the altitude. The magnitude of this force is simultaneously influenced by the altitude of the lift and the development of the processes of filling and stabilizing the hose line over time.

The reactive force of the F_5 jet had smaller values, but its value varied depending on the mode of fire extinguishing agent supply. Fig. 8–10 shows that at an altitude of 40 m, F_5 was 22–33 N for a nozzle with a diameter of 5 mm. For a nozzle with a diameter of 6 mm, the reactive force reached 42–43 N, and for a nozzle with a diameter of 7 mm, it was 44–45 N. At an altitude of 50 m, for a nozzle with a diameter of 5 mm, the F_5 values were 34–49 N, which is shown in Fig. 11. For a nozzle with a diameter of 6 mm, they reached 54 N. When using a nozzle with a diameter of 7 mm, the reactive force was 57 N, according to the results shown in Fig. 13. The highest reactive forces were observed at a pressure of 8 bar and the use of nozzles of 6–7 mm. The increase in F_5 with increasing pressure and nozzle diameter is explained by a change in the hydraulic parameters of the water jet. The increase in the area of the outlet cross section and the change in pressure affect the flow

rate, the outflow velocity and the corresponding pulse flow of the jet. It is by changing the pulse flow that the increase in the reactive load can be explained in the regimes with higher pressure and nozzle diameter. The nature of the change in F_5 is additionally reflected by regression equations (6) and (11) and the calculation surfaces in Fig. 18. For the three studied diameters, the surfaces in Fig. 18 demonstrate a pronounced change in the calculated reactive force over time. This is consistent with the coefficients of the regression model (6) in the coded variables given in Table 5. The largest coefficient of the main effect of this model corresponds to the factor x_1, which characterizes the feed time. The pressure and nozzle diameter also change the value of F_5 and the nature of the response surfaces. The regression model (6) provides for main effects, pair interactions and triple interactions of the studied factors. Therefore, it is advisable to consider the change in F_5 as a result of their joint action, and not as a consequence of a change in one parameter. The results for F_1–F_4 characterize the load distribution between the fire hydrant fastening elements. According to the experimental values in Table 4, the forces F_1, F_2, and F_4 varied within relatively narrow limits. The largest range among the forces in the fastening nodes was established for the force F_3, which characterizes the load in the lower fixing element. This result is consistent with the coefficients of the regression model (4) given in Table 5 and the nature of the calculation surfaces given in Fig. 16. The largest coefficient of the main effect of the regression model (4) corresponds to the factor x_1 and is 8.205. A noticeable contribution to the calculated value of F_3 is also made by the interaction of the factors x_1 and x_2, the coefficient of which is 1.0375. Therefore, the change in F_3 within the limits of the adopted model is primarily associated with the time development of the load and the interaction of the studied factors. The design surfaces for forces F_1, F_2 and F_4 shown in Fig. 14, 15, 17 are characterized by less pronounced changes compared to F_3, which is consistent with regression models (2), (3) and (5). The presence of interfactor interaction in regression models (2)–(6) means that the design effect of one factor depends on the levels of other factors. Therefore, for engineering assessment of forces, it is advisable to use complete regression dependencies, rather than individual model coefficients. The obtained results show that the force load of the studied system cannot be characterized by only one indicator. The reactive force of the jet F_5 and the tension force of the suspended system F_6 have different physical natures. The force F_5 is formed by the reactive action of the jet on the fire hose. The force F_6 is associated with the load of the suspended hose line, the mass of water and the processes accompanying its filling. Therefore, the forces F_5 and F_6 cannot be directly summed arithmetically to determine the required UAV thrust. The required thrust reserve also depends on the mass of the device, the installed equipment, the directions of the forces of their application points. It is also necessary to take into account the position of the fire barrel relative to the center of mass and the ability of the stabilization system to compensate for the created moments.

The obtained values of F_5 and F_6 should be considered as initial external loads for constructing a spatial force diagram of the aircraft. When interpreting the regression models F_1–F_5, it is necessary to take into account the method of forming the initial data. For each point of the factorial plan, values averaged from the results of tests at altitudes of 30, 40 and 50 m were used. This approach made it possible to describe the generalized response of the system within the studied altitude range. At the same time, the construction of the models F_1–F_5 does not provide a separate quantitative assessment of the influence of altitude on each force. Altitude is directly introduced as an independent factor only in the model F_6 with the time of supplying fire extinguishing agent. The effect of altitude on F_5 in this work was evaluated directly from the results of field tests at individual altitudes.

Comparison with known results confirms that the reactive load is determined by the set of hydraulic and structural parameters of the system. In work [7] for a multirotor aircraft, the calculated jet force at a pressure of 120 bar was 18.77 N. In the conducted study, the maximum reactive force F_5 exceeded 54 N. The obtained value is 2.9 times the calculated jet force of 18.77 N given in work [7]. At the same time, a direct quantitative comparison of these values has significant limitations. The systems under study differ in nozzle diameters and geometry, water flow rate, hose line design and feed modes. Therefore, the operating pressure alone cannot uniquely determine the magnitude of the reactive force. When evaluating it, it is necessary to take into account the flow rate, flow velocity, outlet cross-sectional area and other system characteristics. The results of work [8] also show the dependence of the fire nozzle response on the flow parameters, its geometry and hydraulic mode. For the smooth-bore nozzles with a diameter of 22 and 24 mm considered in [8], the calculated reaction values are approximately 230–335 N. These values significantly exceed the maximum force F_5 obtained in the study. A direct comparison of the results is limited by significant differences in nozzle diameters, water flow rates, and jet formation conditions. At the same time, the results of both studies are consistent with the physical relationship of the reactive force with the parameters of the water flow and the nozzle geometry. Even at lower absolute values, F_5 remains an external load that must be taken into account for UAVs. In addition to the translational action, the reactive force can create a moment relative to the center of mass if its line of action does not pass through it. The magnitude of such a moment depends on the point of application of the force, its direction, and the spatial location of the fire hose. The results of [9] show that the load associated with the fire hose line is determined not only by the nozzle reaction. In [9], the dependence of the force effect on the configuration of the hose, its spatial position, and the method of holding it was established. This is consistent with the established increase in F_6 with increasing altitude of the suspended hose line. For the studied system, this result justifies the need to separately consider F_6 when determining external loads. The reactive force F_5 and the tension force F_6 are formed by different physical processes and affect the aircraft differently. An important methodological decision was to measure the pressure directly in front of the fire hose. This approach makes it possible to link the measured forces with the actual hydraulic conditions at the entrance to the fire hose. In [10], the dependence of pressure losses on the internal diameter and characteristics of the internal surface of the fire hose is shown. Due to hydraulic losses, the pressure at the outlet of the pumping equipment does not uniquely characterize the operating conditions of the nozzle. Therefore, pressure control in front of the fire hose reduces the uncertainty associated with head losses in the hose line. The peculiarity of the conducted study is the simultaneous determination of the jet reactive force and the tension force of the suspension system at altitudes of 30–50 m. Unlike the works [7, 16–18], not only the jet reactive force was investigated, but also the load from the suspended hose line. This approach allows to consider the force load as the result of the joint action of components that

have different physical natures. The obtained field data were supplemented with regression dependencies intended for the quantitative description of the force parameters within the studied regimes. At the same time, the obtained results have certain application limits. Regression dependencies (7)–(11) were obtained for the factor space $t = 4–24$ s, $p = 4–8$ bar and in $d = 5–7$ mm. Extrapolation of these models beyond the studied intervals without additional experimental verification can lead to unfounded estimates of the force parameters. Regression model (17) was obtained for the force F6 in the altitude range of 30–50 m and time levels of 4.14 and 24 s. The full factorial design used to construct regression models (2)–(6) is saturated. In it, 8 regression coefficients of the model are determined by eight combinations of extreme levels of three factors. With such a structure, the exact reproduction of values in the nodes of the plan is a mathematical property of the adopted model. Therefore, it does not in itself confirm the statistical adequacy of its functional form. The assessment of experimental error and reproducibility can be based on the test results. Verification of the functional adequacy of the models requires independent control points or expansion of the experimental design.

The limitations of the study also include the use of an experimental unit instead of UAV in real flight conditions. The developed unit reproduced the main force interactions between the fire hose and the hand-held line. At the same time, it did not reproduce the dynamic response of a real aircraft, and the operation of its test system was performed under controlled conditions without the influence of high-temperature convective flows, smoke, wind loads, and pronounced atmospheric turbulence. Therefore, the obtained force values should not be directly interpreted as an assessment of the spatial stability of a specific UAV model. They should be used as initial engineering data for further modeling, design, and testing of the stabilization system. A separate drawback of the approach used is the averaging of the F_1–F_5 values based on the test results at three altitudes. Because of this, altitude is not included as an independent factor in the corresponding regression models. This approach allowed obtaining generalized dependencies for the altitude range of 30–50 m, but limited the possibility of quantitatively isolating the influence of altitude. Another drawback is the lack of independent control points to verify the adequacy of the functional form of the saturated models F_1–F_5. Eliminating this drawback requires expanding the experimental design and performing additional tests at points that were not used to determine the coefficients. To clarify the obtained regression dependencies, it is advisable to include altitude as an independent factor in the models F_1–F_5. This will require expanding the factorial design and a corresponding increase in the number of experimental combinations. A promising direction is to conduct tests with a real UAV in flight. Such studies will make it possible to assess the response of the stabilization system to the measured external forces and the moment created by them. It is also advisable to verify the obtained models at independent control points and under conditions close to real fire extinguishing. Future studies will be conducted with other types of fire extinguishing agents, in particular compression foam.

The results obtained create the basis for substantiating the design parameters of the UAV and the permissible modes of fire extinguishing agent supply.

The established dependencies can also be used when forming requirements for stabilization systems taking into account the reactive force and load of the suspension system.

The main experimental difficulties of such development are associated with ensuring reproducible modes of fire extinguishing agent supply and controlled measurement of forces at altitude. An additional difficulty will be the simultaneous registration of external loads and the dynamic control system of the UAV. Thus, the regularities of the formation of force loads within the studied modes of fire extinguishing agent supply have been experimentally established.

7. Conclusions

1. An experimental unit has been developed to study force loads during the supply of fire extinguishing agents through a fire hose, simulating its retention by a UAV. The unit provides simultaneous determination of forces in the fire hose mounting nodes F_1, F_2, F_3, F_4, jet reactive force F_5 and suspension system tension force F_6. A feature of the developed unit is the ability to separately determine the reactive load and the load transmitted through the suspended hose line, as well as automatic fixation of their values.

2. According to the results of experimental studies of force loads during water supply through a fire hydrant at altitudes of 30–50 m, it has been established that the greatest value was the tension force of the suspension system F_6, which at an altitude of 50 m was 420–430 N. With an increase in the lifting altitude from 30 to 50 m, the force F_6 increased by 19.6%, while the change in the pressure in front of the fire hydrant and the diameter of the nozzle did not have a decisive influence on its value. An increase in pressure from 4–8 bar and a nozzle diameter from 5–7 mm was accompanied by an increase in reactive loads. It was experimentally established that with an increase in the diameter of the nozzle from 5 to 7 mm at all studied pressure values, the forces F_1, F_2, F_3, F_4 increased by 7–9%, and the reactive force of the jet F_5 by 92–96%, which is consistent with theoretical hydraulic calculations. The results obtained confirm the need to simultaneously take into account the jet reactive force and the load from the suspended hose line, which have different physical natures. At the same time, to determine the resulting load on the UAV, it is necessary to take into account not only the absolute values of the forces, but also the directions of their action.

3. Based on the full factorial experiment, the regression dependence of the forces F_1–F_5 has been obtained, which takes into account the influence of the water supply time, the pressure in front of the fire hydrant and the diameter of the nozzle. It has been established that the nature of the influence of the studied factors differs for individual components of the force load. The most pronounced change among the forces in the fire hydrant fastening nodes was established for the force F_3, while the forces F_1, F_2 and F_4 were characterized by relatively minor changes. The jet reactive force F_5 was also characterized by a significant change depending on the factors under study. The obtained regression models allow to quantitatively assess the force loads F_1–F_5 depending on the combination of the water supply time, the pressure in front of the fire hydrant and the diameter of the nozzle.

4. A quadratic regression model of the tension force of the suspended system F6 was constructed, which describes its dependence on the water supply time and the lifting altitude. It was established that the force F_6 increases with an increase in the duration of water supply and the lifting altitude, and the nature of its change is nonlinear. The increase in the tension force with increasing altitude is explained by an increase in the length of the suspended hose line and the mass of water

contained in it, and the dependence on time is explained by the processes of filling the hose line and stabilizing the water supply mode. The obtained quadratic model allows to estimate the load from the suspended system depending on the water supply time and the lifting altitude.

5. According to the results of the analysis of the response surfaces of the forces F_1–F_6, the peculiarities of the influence of the studied factors on the formation of force loads were established. It was determined that the nature of the change in the forces F_1–F_5 depends on the joint influence of the water supply time, the pressure in front of the fire hose and the diameter of the nozzle, while for the force F_6 the determining factors are the water supply time and the lifting altitude. The limits of application of the obtained regression models for forces F_1–F_5 within $t = 4$–24 s, $p = 4$–8 bar, $d = 5$–7 mm are established. For model F_6, the investigated altitude range is 30–50 m, and the duration of water supply is 4–24 s. The obtained models allow to estimate force loads and to justify the permissible water supply modes and design parameters of the UAV. The next stage of the study will be aimed at estimating force loads during the supply of air-mechanical foam as a fire extinguishing agent.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, authorship or other, which could affect the study and its results presented in this article.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

During the preparation of the manuscript, the authors used the ChatGPT artificial intelligence model (OpenAI, GPT-5.5) as an auxiliary tool for performing editorial, linguistic and bibliographic tasks. AI tools were used in the sections "Literature Review and Problem Statement" and "References", as well as for linguistic editing. In particular, artificial intelligence was used to improve the academic style of presentation, linguistic editing of individual fragments of text written by the authors. All results obtained using AI tools were verified by the authors based on scientific publications, engineering reports, and experimental data obtained within the scope of the study. All numerical results, computational models, engineering assumptions, figures, interpretations, and conclusions were generated, verified, and validated directly by the authors. AI tools were not used to generate research ideas, goals, objectives, methodology, experimental data, data processing, computational models, figures, tables, numerical results, interpretation of results, discussion logic, or study conclusions. The use of AI tools did not affect the scientific conclusions of the study and was limited to supporting editorial, linguistic, and bibliographic tasks during manuscript preparation.

Authors' contributions

Andrii Gavryliuk: Conceptualization, Methodology, Supervision, **Ihor Kaluzhniak:** Conceptualization, Writing – Original Draft, Visualization, Data curation; Methodology; **Ivan Parubchak:** Project administration, Supervision, **Illya Zhidenko:** Project administration, Supervision, Resources; **Tetiana Voitovych:** Writing – Review & Editing, Formal analysis, Investigation, Resources; **Alona Mykhailova:** Project administration, Supervision, Resources.

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