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Article

Results of the Study of the Influence of External Cargo Parameters on the Helicopter Controllability

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Abstract: Helicopters are widely used for air transportation and aerial work with cargo on external cables, one of the most challenging and dangerous uses. The main reason for the flight complication is the change in the controllability characteristics of the helicopter because of the presence of cargo. As of today, flight tests are mainly conducted to determine the feasibility of aerial transportation and aerial work involving external cargo. In addition, they are conducted to determine safe flight regimes when performing such operations. From a flight safety perspective, it is always desirable to know the changes in the control parameters before flight tests are performed. A proposal was made to use theoretical methods, including numerical simulations, to solve these problems. At present, work is progressing to isolate the effects of different cargoes on the external cable suspension and its direct effects on the static and dynamic characteristics of the helicopter's control and stability. The effect of cargo mass and sail weight on the control efficiency is expressed by the helicopter's angular acceleration, which is gained by deviating the cyclic pitch handle—a static control and stability indicator. When considering dynamic control and stability, the influence of the length of the external suspension cable on the transition time was investigated. The results obtained were refined for inclusion in all flight manuals for Mi-8 helicopters concerning flights with cargoes attached to the external suspension cables, the size and weight of the suspension cables as well as the methods of instruction and for preparing the crew for flights with upgraded cargo, including instruction via flight simulators.

Keywords: helicopter; mathematical model; controllability; cargo on the external sling

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1. Introduction

Cargo transportation on helicopters' external sling (HES), shown in Figure 1, is one of the most complex uses of helicopters. We know this based on theoretical studies devoted to this problem and from the practice of flying helicopters [1–7]. Due to the cargo on the external sling (ES), the helicopter controllability characteristics have changed, and the nature and magnitude of this change are determined by both the cargo's parameters and the length of the cable on which it is suspended.

At present, flight tests are mainly used to determine the feasibility of performing air transportation and aerial work with the use of ES and safe flight modes during their flight check (FC). This is due to the change in controllability caused by cargo on the ES (HES). For example, FAR Part 133—Rotorcraft external—cargo operations, which applies in the USA and is dedicated to regulating helicopter flights with Hover [8], requires a test flight with each variant of the "helicopter HES" system to confirm acceptable controllability. This is because of the need to have information about the influence of the cargo on controllability and the need to assess the possibility of flight itself and prepare the crew for this change in controllability parameters.

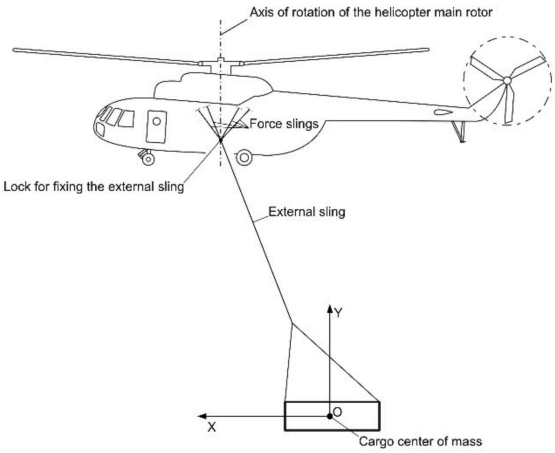

Figure 1. Helicopter with cargo on the external sling.

From the point of view of flight safety, it is desirable to know the change in controllability parameters before performing an FC. To solve this problem, theoretical methods such as inclusion are used. The advantage of this method is the expansion of flight modes available for research, reducing the time and cost of research, as well as the ability to set the entire range of parameters of the cargo and the HES as a whole.

The present article describes the results of the study of the influence of the Mi-8MTV helicopter HES parameters on its controllability by employing numerical simulation using special software developed by the authors of this article. Some technical characteristics of the Mi-8MTV helicopter are given in Table 1.

Table 1. Main technical characteristics of the Mi-8MTV helicopter [9].

Parameter Title	Quantity
Maximum flight speed, km/h	240
Maximum flight range, km	1100
Maximum takeoff weight, kg	13,000
Maximum weight of the cargo on reinforced external sling, kg	5000
Service ceiling, m	4800

The Mi-8MTV helicopter uses a point external sling Figure 1. Inside the cargo compartment, they suspend a lock on four cables for attaching an external sling that passes through a hatch in the cabin floor. The sling is attached to the hook of the lock, and this part of the fastening is hinged, arranged at a single point.

This article discusses the effect of the following parameters of the external sling on the controllability of a helicopter:

- cargo weight;
- ballistic coefficient of the cargo, characterizing the windage of the cargo (discussed below in this article);
- the length of the external sling (distance from the external sling fastening lock to the cargo center-of-mass) (Figure 1).

The data got in computational experiments on changes in controllability techniques can serve for the compilation of flight manuals for the Mi-8 helicopter and its modifications concerning flights with HES, as well as for the methods of crew training for flights with new cargo, including flight simulators.

2. Research Method Description

In this work, the influence of HES on static and dynamic indicators of helicopter controllability was studied.

As a static indicator of controllability, we chose the relative efficiency of control, which refers to the ratio of the increment of control moment per unit of control lever deviation to the moment of inertia of the helicopter relative to the corresponding axis of the associated coordinate system, which is equivalent to the angular acceleration around this axis [10]:

$$\overline{M}^{\delta}_{\text{ctrl}} = \frac{\Delta M_{\text{ctrl}}}{\Delta\delta \cdot I} = \varepsilon, \tag{1}$$

where,

ΔM_{ctrl}—control torque increment;
$\Delta\delta$—control lever deviation from the balancing position;
I—helicopter axial moment of inertia;
ε—helicopter angular acceleration.

Thus, the angular acceleration of the helicopter resulting from the deviation of the control lever is an indicator of controllability—control efficiency. However, it should never be assumed that the higher the efficiency of management, the better. For ease of control and flight safety, it seems desirable that the efficiency of control does not change much when the helicopter cargo and flight conditions change.

The practice of flying helicopters with HES and theoretical studies show [1,10] that the efficiency of helicopter pitch and roll control increases in comparison with a helicopter without HES, including in comparison with a helicopter with a similar cargo in the cargo hold. When comparing a helicopter without cargo and a helicopter with cargo (both in the freight compartment and on the ES), this is explained by an increase in thrust of the main rotor, which in the second case leads to a larger increase in the control moment at the same deflection of the cyclic pitch stick. When comparing a helicopter with cargo inside the cargo cabin and a helicopter with HES, this is explained by the decrease in the second case of the helicopter's moments of inertia relative to the longitudinal and transverse axes, which, with the same control moment increments will lead to a much higher angular acceleration of the helicopter with HES [11].

However, the maximum angular acceleration gained by the helicopter when the control lever is deflected is a static indicator of controllability. However, to assess controllability, dynamic indicators are also relevant, which include, for example, the transient time t, which can be defined as the time interval, after which the deviation of the observed motion parameter will differ from its final steady-state value by only a predetermined value, for example, by 5%. The cyclic pitch stick movement was chosen as the observed parameter because this parameter most fully characterizes the pilot's work. The limit value, after reaching the observed parameter, is considered to be steady ±5 mm of the cyclic pitch handle travel in each channel (roll and pitch), which is 3% of the maximum deviation.

In performing this work, parametric studies were conducted to determine the influence of the parameters of the cargo and ES as a whole on the relative effectiveness of controlling the angular position of the helicopter around the longitudinal and transverse axes (respectively), as well as on the transient time t.

One of the world's most mass-produced helicopters, the Mi-8, was chosen as the object of study.

To study the dynamics of the flight of any aircraft, especially at the limits of flight modes, including the system "helicopter—HES", the most rational use of theoretical methods is mathematical modeling, which is devoted to many works [12–28].

When conducting the present study, the authors used a previously developed mathematical model of the flight dynamics of the "helicopter—HES" system [2,29] and the corresponding software—the software package Helicargo, consisting of the Helicopter software module, which simulates the Mi-8MTV helicopter, and the Cargo software module, which simulates the HES. Both modules use so-called "grid" models, in which the aerodynamic characteristics of the helicopter and cargo are specified at certain steps as multidimensional arrays depending on the flight parameters. The linear interpolation method is employed to calculate the intermediate values of the characteristics.

Helicargo software developed by the specialists of the Moscow State Technical University of Civil Aviation (Moscow, Russia) allows simulating the helicopter and HES flight in 3D space (helicopter and HES angular position relative to the ground and velocity vector of incoming airflow, as well as trajectory motion—the movement of the helicopter and HES centers of mass as material points relative to the starting coordinate system). The above mathematical model, based on which this software package was created, was tested for adequacy, which was reflected in the following publications: [30–32].

3. Results and Analysis

3.1. Influence of Cargo Mass on the Relative Efficiency of Control

Computational experiments performed by the authors have shown that the relative control efficiency, estimated by the angular acceleration gained by a step deviation of the cyclic pitch handle, increases with increasing HES mass, other conditions being equal.

Figures 2 and 3 show the dependence of the increment of the angular acceleration of the Mi-8MTV helicopter with an external sling on the cargo mass in comparison with the option of placing a cargo of the same mass inside the cargo compartment and in comparison with a helicopter without cargo with an instantaneous movement of the cyclic pitch handle by 50 mm from the neutral position, respectively, in pitch and roll.

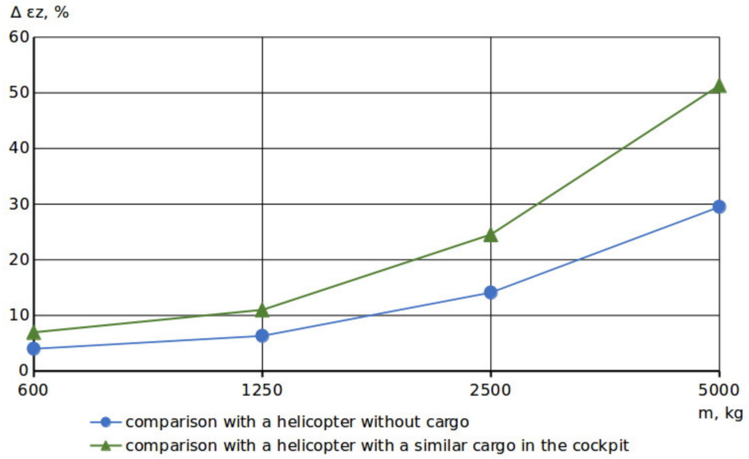

Figure 2. Influence of mass on-pitch angular acceleration.

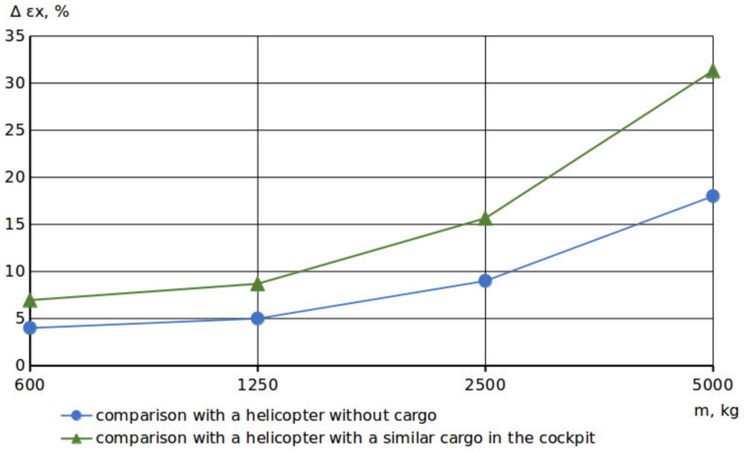

Figure 3. Influence of cargo mass on roll angular acceleration.

The graphs above show that the HES gives a significant increase in angular acceleration when the cyclic pitch stick is tilted, which makes the helicopter control more "responsive control". This means that the helicopter becomes more sensitive to control lever deviations, i.e., when the control stick is deflected by the same amount, the angular acceleration of pitch or roll becomes more pronounced.

The graphs above show that the presence of the HES gives a significant increase in angular acceleration when the cyclic pitch stick is tilted, which makes the helicopter control more "responsive control", this means that the helicopter becomes more sensitive to control lever deviations, i.e., when the control stick is deflected by the same amount, the angular acceleration of pitch or roll becomes greater.

3.2. Influence of Cargo Surface Area on Relative Steering Efficiency

The surface area of the cargo estimated by the ballistic coefficient of the cargo [33]:

$$c = \frac{c_x S}{m}, \tag{2}$$

where,

c_x—coefficient of the longitudinal aerodynamic force of the cargo, the aerodynamic force acting along the OX axis of the coordinate system associated with the cargo Figure 1;
S—typical cargo surface area;
m—cargo weight.

When estimating the effect of cargo floatation on the relative efficiency of control, the mass of the cargo is assumed unchanged. Therefore, in this case, the ballistic coefficient of the cargo can change only because of changes in the coefficient of the longitudinal aerodynamic force of the cargo. This is also true for its characteristic area.

Since an increase in the surface area of the cargo entails an increase in the aerodynamic drag force, and hence an increase in the cable tension force ES, increasing speed will increase the efficiency of control, expressed through the maximum angular acceleration in both the roll channel and the pitch channel.

Table 2 below shows the speeds at which the effect of cargo surface area becomes noticeable as a function of the ballistic coefficient for ball-shaped cargo.

Table 2. Parameters of cargo and flight speed, at which the influence of the surface area of the cargo was revealed.

Ballistic Coefficient, m^2/kg	0.0025	0.005	0.01	0.02
Speed of onset of surface area effect on relative pitch control efficiency, km/h	160	120	90	60
Speed of beginning of the influence of surface area on relative roll control efficiency, km/h	–	160	140	100

Figures 4 and 5 show the dependence of the increment of the angular acceleration of the Mi-8MTV helicopter with an external sling on the ballistic coefficient of the cargo in comparison with the option of placing the cargo of the same mass inside the cargo compartment and in comparison with a helicopter without cargo with an instantaneous movement of the cyclic pitch handle by 50 mm from the neutral position, respectively, in pitch and roll.

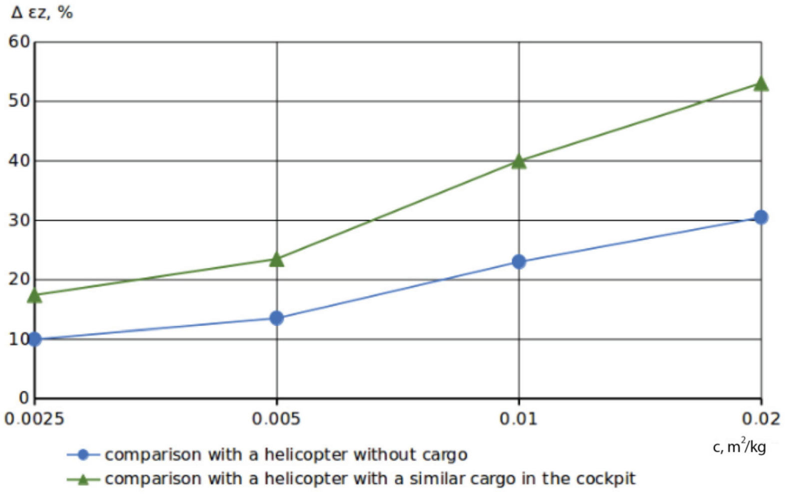

Figure 4. Influence of ballistic coefficient of cargo on pitch angular acceleration.

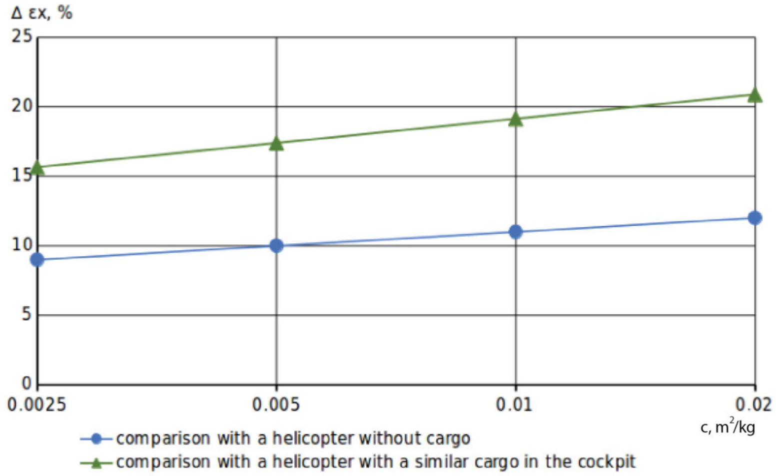

Figure 5. Influence of ballistic coefficient of cargo on the angular acceleration of roll.

4. Influence of External Sling Length on Transition Time

The effect of ES cable length L on the transient time t is clear at certain combinations of mass m and ballistic coefficient of the cargo c. The values of the transient time increment t with HES, expressed as a percentage of the transient time without HES, depending on the cable length, are shown in Figure 6. Computational experiments were conducted in which the virtual pilot was tasked with accelerating from a steady-state horizontal flight with no oscillations of the helicopter or cargo to build these graphs. From 40 km/h to 100 km/h, and braking from a steady horizontal flight from 100 km/h to 40 km/h. Based on the results of the experiment, the transient time was determined, and we found its average value for acceleration and deceleration for the cargo parameters and cable length.

Experiments were conducted with compact lightweights, having c = 0.0025–0.005 m^2/kg and m = 600–2500 kg, from which it is rational to choose the shortest possible cable length ES L because with decreasing cable length for such weights the time of transient during acceleration and braking decreases. For heavy, large substantial surface area cargo, the effect of cable length was not significant.

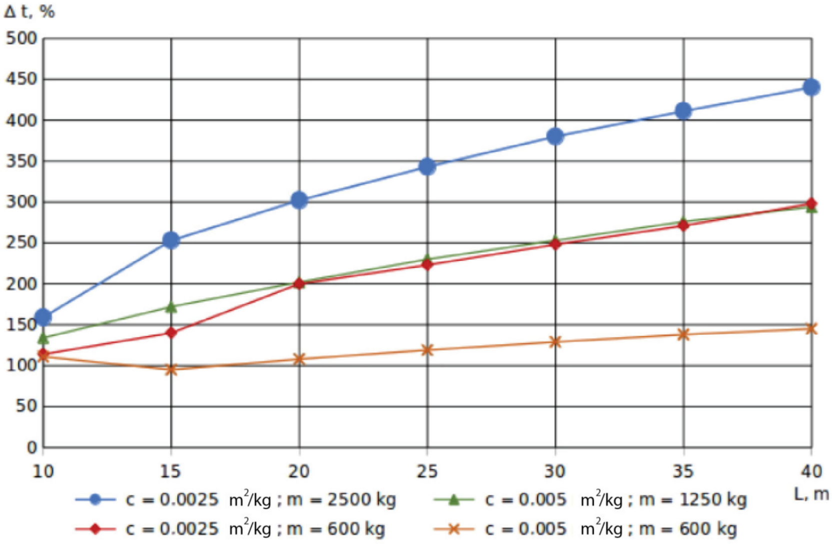

Figure 6. Influence of cable length on transient time.

5. Conclusions

The results of the study of the influence of external cargo parameters on helicopter controllability show that the relative control efficiency, expressed in terms of the maximum angular acceleration of the helicopter, is influenced by the weight of the cargo and its surface area. With both an increase in mass and an increase in cargo surface area, the relative efficiency of control increases. A helicopter made ”rigorous” in control can make it much more difficult to control it.

In addition, a study of the influence of external suspension cable length on dynamic controllability was conducted, which showed that for the transportation of light cargo with a small surface area, chose the shortest possible length of cable, based on the exclusion of the possibility of collision of the cargo with the helicopter structure. For heavy (over 2500 kg), large surface area cargo (with a ballistic coefficient of over 0.005 m^2/kg), the effect of cable length was not significant.

Based on the results, additions are planned to the flight manual of the Mi-8 helicopter and its modifications, which will allow the crew to assess the feasibility of the flight on the planned modes and prepare the crew for changes in controllability before performing a flight with cargo on the external sling.

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