Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 38, 2026, Sofia

DOI: https://doi.org/10.3897/arb.v38.e22

ENSURING THE SAFETY OF A HELICOPTER WITH AN EXTERNAL FIRE EXTINGUISHING DEVICE FOR EXTINGUISHING FIRE IN EXTREME METEOROLOGICAL CONDITIONS IN FLIGHT

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Key words: *helicopter, external fire extinguishing device, flight, balance, fluctuations*

Abstract

Methods for stabilizing the external device have been investigated and proposed based on the study of the mechanism for the occurrence of oscillations of the external device and the mathematical description of the dynamics of movement of the "Helicopter–external fire extinguishing device" system, consisting of synchronizing the movement of the helicopter and the external device in flight and creating a rotational movement of the device around the vertical axis coinciding with the central cable for attachment to the helicopter.

Introduction

Over the past two decades, the role of aviation in combating forest fires has been increasing, as fires are becoming more numerous, threatening larger areas and settlements. Along with the use of specialised aircraft, the use of various types of helicopters and various types of external fire extinguishing devices of the “Bambi Bucket” type (“BB4453”, “BB5566”, “BBHL5000”, etc.), manufactured by SEI Industries LTD, Canada [1], is increasing. In the Republic of Bulgaria, one Mi-17 helicopter and several AS532AL Cougar helicopters [2] with an external fire extinguishing device “BB4453” with a capacity of 2,000 l are used in fire extinguishing operations. However, the prediction of the behaviour of the external fire extinguishing device during dynamic changes in helicopter flight parameters in the environment is carried out primarily based on the experience of individual flight crews. This is because the dynamics of the external fire-extinguishing device in the flight of a firefighting helicopter have not yet been studied in sufficient depth.

To increase the safety of helicopter firefighting with an external fire-extinguishing device, it is necessary to thoroughly study the characteristics of the external device's dynamic stability and their effect on helicopter behaviour in flight. Then, it is necessary to develop a set of methods, techniques, and modes of using a helicopter with an external fire-extinguishing device for performing aviation activities in extreme conditions, such as extinguishing forest fires, especially fires located in mountainous areas with highly rugged terrain.

Main issues for the flight dynamics of a helicopter with an external fire-extinguishing device

One of the main problems is the identification of airflow disturbances taking into account the complex aerodynamics of the flow around the blades of the main propeller, fuselage, and tail rotor, as well as the identification of the characteristics of the aerodynamic flow around the external device. Another main problem is the determination of the boundaries of the dangerous zones for the deviation of the moving elements of the structure relative to the external fire-extinguishing device, for warning when approaching critical and emergency situations.

It is necessary to study the processes and develop effective methods for extinguishing the oscillations of the external device in flight. Methods for manoeuvring the helicopter with an external fire-extinguishing device must be developed and subsequently tested in aviation practice. It is necessary to study the process of "falling" of the helicopter in flight, in which the length of the central cable for attaching the external device to the helicopter changes almost instantly, which affects the oscillation period of the external fire-extinguishing device.

To study the dynamic motion of a helicopter with an external fire-extinguishing device, it is necessary to develop complex mathematical models. In the considered system “Helicopter–External Fire Extinguishing Device”, in complex spatial motions, the degrees of freedom reach almost fifty. The Lagrange-2 method is not suitable for solving differential equations of motion of systems with many degrees of freedom and a set of non-potential forces, especially in the case of control systems with feedback-based regulation algorithms.

One of the most important issues for ensuring the safety of firefighting flights with helicopters and external devices is the creation of aviation simulators for training flight crews, in which the aerodynamics and flow dynamics of the helicopter and the external device can be reproduced as a dynamic system with many degrees of freedom, under non-potential forces and control effects.

Developing methods to dampen oscillations of an external device attached to a central cable on a helicopter in flight is very important because the helicopter has some of the most difficult and dangerous flight modes to control. These dangers associated with helicopter control in flight increase when the helicopter is considered as a single system with the fire-extinguishing device.

On the other hand, there are requirements in several international documents developed by international and national organisations [3–6] that require further research into the issues of formalising procedures for assessing aviation safety when performing helicopter flights with an external fire-extinguishing device for extinguishing fires. The International Civil Aviation Organisation (ICAO) develops standards, regulations, procedures, and recommended practices on aviation safety, which are disseminated to aviation operators worldwide.

Aircraft flight safety assessment based on ICAO standards

ICAO Annex 19 contains comprehensive provisions applicable to safety management functions related to or in direct support of the safe operation of aircraft. It emphasises the importance of State safety management in several aviation areas [7]. The annex provides recommendations to complement the State (national) Safety Programme (SSP) and Safety Management System (SMS) frameworks. The annex also includes recommendations (provisions) for State monitoring and oversight of aviation safety (through specialised State bodies), as well as an obligation to collect, analyse, exchange and protect safety information.

Safety Management Standards and Recommended Practices are designed to assist States in managing aviation safety risks, in coordination with their service providers [8]. Given the increasing complexity of the global air transport system and its interconnected aviation activities required to ensure the safe operation of aircraft, safety management provisions support the continuous development of a proactive safety improvement strategy. The foundation of this proactive safety strategy is based on the development and implementation of a State Safety Programme (SSP) that systematically addresses safety risks, consistent with the implementation of safety management systems (SMS) by service providers.

ICAO guidance documents on the principles and concepts of safety management, the State Safety Programme (SSP) and the implementation of the safety management system are contained in the ICAO Safety Management Manual (SMM) (Doc 9859) [9]. To respond to the needs of the diverse aviation community implementing safety management and to new recommendations arising from the materials, discussions, and views expressed at the second High-Level Safety Conference held in 2015, a supplement to the 4th edition of the SMM has been developed.

The other related and applicable aviation safety document is the international standard ISO-8402:1994 [10]. It provides definitions and terms related to quality management and quality assurance, as well as tools and techniques for quality assurance and management.

The following definition is adopted in Doc 9858-AN/460: "*Flight safety is a state of the aviation system in which the risk of causing harm to property or personnel does not exceed an acceptable level*".

From the analysis of the accepted concept of flight safety, it follows that "*risk is such a state with predictable (definable) possible harmful consequences for the elements of the system in the studied flight situations, provided that in the system under some threats a dangerous (or risky) random event R with negative* *consequences of the type of loss H_R may occur*". The concept of risk assessment R is mathematically defined by the following formula [11]:

(1) $$R = A_*\left(\omega_\xi \middle| \mu_1, H_R, \Sigma_0\right),$$

where: A_* is an event with a criticality sign ($*$), separated from the set of possible events $A_* \epsilon \{A_i\}$
ω_ξ is an elementary event with a randomness symbol;
μ_1 is an indicator of the randomness frequency, i.e. how often events of type A_* occur;
Σ_0 is a set of conditions that characterise the functioning of the aviation system, for example, "a helicopter with an external fire extinguishing device in flight to extinguish natural fires".

Research shows that formula (1) is universal for many types of air transport. It allows the level of aviation safety for the helicopter to be determined by the level of danger, which determines the significance (level) of the risk as the value of $\hat{R}$ - an integral function of the estimated amount of danger in the studied aviation system:

(2) $$\hat{R} = \hat{f}(\mu_1, \overline{H}_R | \Sigma_0).$$

In this regard, it is important to establish the adequacy of aviation practice to the following recommendations:

- influence of the helicopter on the dynamics of swinging of the external fire extinguishing device as a pendulum [12]. It is known that if the complex aerodynamics of the flow around the external device are not taken into account, the influence of the helicopter is not significant, especially at small initial angles of deviation of the central cable of the device from the vertical position;
- the mutual influence of the dynamics of the two components of the connected system "Helicopter-external fire extinguishing device" without external critical disturbances is sufficiently reliably described as a conservative dynamic system without damping using the model of an ideal spherical joint [12];
- to assess the influence of the "failure" of the central cable attachment point of the external device on the magnitude of the device's oscillations, which will allow the crew to determine control modes when manoeuvring to extinguish the oscillations.

Of interest is the determination of the degree of influence of the movement of the point of attachment of the central cable to the helicopter on the studied system "Helicopter-external fire extinguishing device" and for assessing the possibilities for damping the oscillations of the external device.

Some practical methods and means for combating the longitudinal-transverse swing of the external device are known: reducing the flight speed; creating vertical and horizontal acceleration of the helicopter, i.e., changing the movement characteristics of the central cable attachment point. In this case, it is important to study and determine how the central cable attachment point of the external device should move to extinguish the oscillations of the external fire-extinguishing device as quickly as possible.

Damping of external fire extinguishing device oscillations in flight

Let us consider the dynamics of the behaviour of two absolutely rigid bodies connected by an ideal spherical joint (Fig. 1). In the diagram in Fig. 1, body No. 1 (m_1) is a supporting body, and body No. 2 (m_2) is located below body No. 2 (relative to the Earth), and we will call it a suspended body.

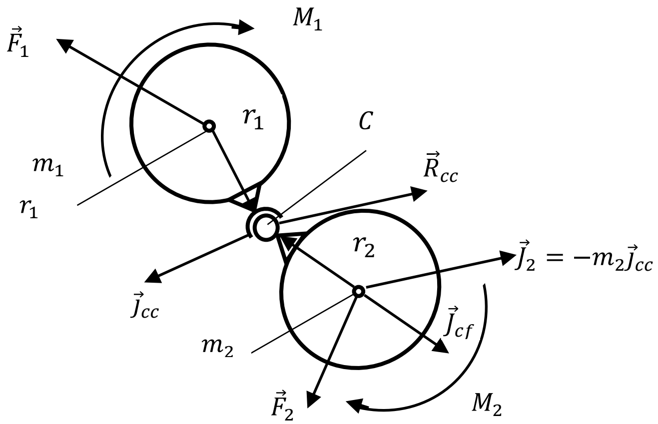

Fig. 1. Diagram of the interaction of two absolutely rigid bodies connected to each other by an ideal spherical joint

Since an ideal spherical joint connects the two bodies, the interaction between them can be described by only one force – $\vec{R}_{cc}$, applied at the joint. As a result, the equations of motion of the system of these two bodies can be written as follows, with the force $\vec{R}_{cc}$ represented as an external force for each of the bodies.

As aviation practice shows, the main tool for damping oscillations is improving helicopter control manoeuvres, the main manoeuvre being the movement of the attachment point to the position of the external device. Thus, the problems with damping oscillations are contained not in the dynamic system itself, but in the complex manoeuvres of the helicopter and external influences (wind gusts, rotation of the device, etc.).

It is known from theoretical mechanics that the dynamics of motion of a closed independent mechanical system with two degrees of freedom is nonlinear:

$$(3) \qquad \frac{(F_1+F_2)}{g}\ddot{x} + \frac{F_2}{g}a\ddot{\varphi}\cos\varphi - \frac{F_2}{g}a\ddot{\varphi}\sin\varphi = 0,$$

$$(4) \qquad I_{cf}\ddot{\varphi} + \frac{F_2}{g}a\ddot{x}\cos\varphi = F_2 a\sin\varphi.$$

After some transformations and partial linearization, we obtain:

$$(5) \qquad (F_1 + F_2)\ddot{x} + F_2 a\ddot{\varphi} - F_2 a\ddot{\varphi}^2\varphi = 0,$$

$$(6) \qquad I_{cf}\ddot{\varphi} + \frac{F_2}{g}a\ddot{x} + F_2 a\varphi = 0.$$

The frequency of natural oscillations of the individual elements in antiphase around the centre of mass depends on the length of the central cable l_{cc} and the ratio of the masses m_1 and m_2.

Maneuvering methods to suppress oscillations of the external fire-extinguishing device

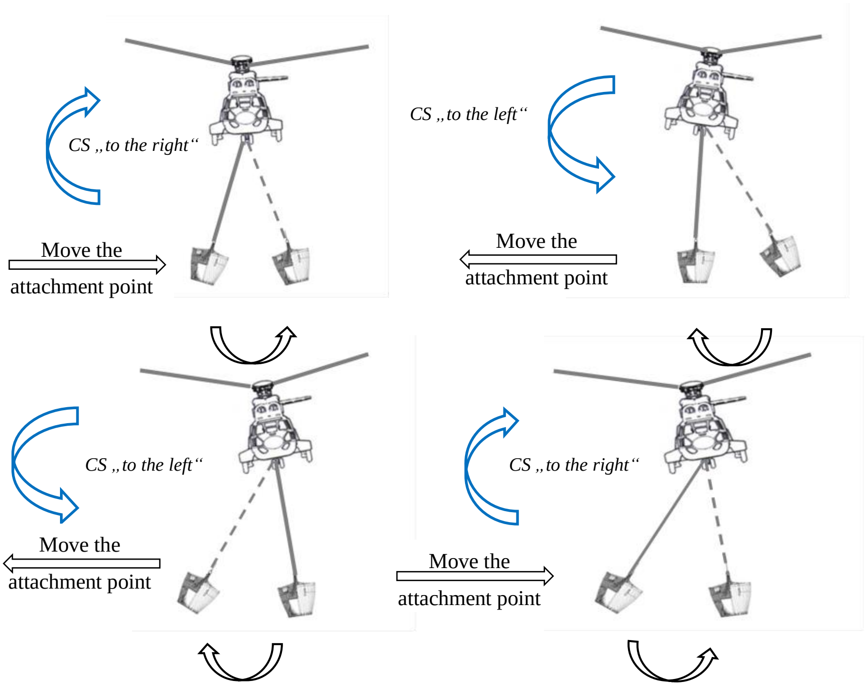

Fig. 2. Maneuvering scheme for extinguishing transverse oscillations of the external fire extinguishing device using the Cycle Stick

Several scientific studies [13–15] confirm that the "Helicopter–external fire extinguishing device" system is a conservative dynamic system without damping. The main method for damping the oscillations of the external device is to control the helicopter by moving the Cycle Stick (CS) to perform manoeuvres to "move" the attachment point of the central cable of the device to the helicopter in all phases of oscillations.

The most general and rational way to extinguish the lateral sway of the external device is (if possible) synchronisation of the movement of the helicopter and the external fire extinguishing device [16, 17], as shown in Fig. 2. For example, if the external device in the process of swaying has "moved" to the right with a sufficiently large amplitude and period of oscillation. The crew should create a right bank and glide, and in this way try to "catch up" with the device. With the next movement to the left, the next "catch up" can be done faster and easier.

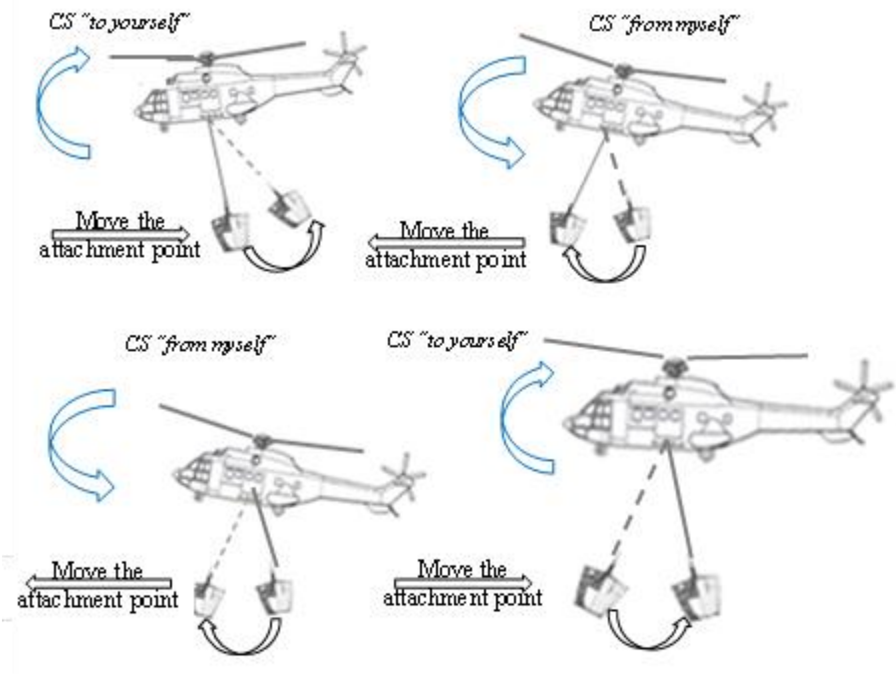

Fig. 3. Manoeuvring scheme for extinguishing longitudinal oscillations of the external fire extinguishing device

A similar method can be applied to eliminate the longitudinal sway of the external fire-extinguishing device, as shown in Fig. 3. The only difference is that the longitudinal oscillations of the external device are significantly more dangerous for the safe completion of the flight. This is due to the fact that in order to "calm down" the oscillations, it is necessary to apply multidirectional movements of the helicopter control stick in the longitudinal direction, so that by changing the pitch angle $\vartheta,_{1}$ a normal (vertical) force can be created for the "Helicopter–external fire extinguishing device" system. However, these manoeuvres pose a potential danger of the main propeller blades approaching the tail propeller blades. It should be noted that such a method of extinguishing oscillations is significantly complex for the flight crews and requires significant professional experience and long-term training in helicopter piloting techniques.

Conclusion

To improve the algorithm for performing aviation procedures for extinguishing natural fires with a helicopter with an external fire-extinguishing device and to increase the productivity of activities, it is proposed to use a technology for working in the fire area in pairs. While one helicopter fills the "BB4453" with water, the other helicopter empties its external device in the fire area. Then the first helicopter flies to the fire area, and the other flies along the route to fill the "BB4453" with water, etc.

Based on the study of the mechanism for the occurrence of oscillations of the external device and the mathematical description of the dynamics of the movement of the "Helicopter-external fire extinguishing device" system, methods for stabilising the external device in flight have been proposed. This involves targeted control-unit movement to synchronise the helicopter and the external device in flight and create rotational motion around the vertical axis, coinciding with the central cable for attachment to the helicopter.

The possibility of extinguishing the oscillations of the external fire-extinguishing device by performing manoeuvres by the helicopter flight crew has been studied. Recommendations have been developed for eliminating the longitudinal and transverse oscillations of the external fire-extinguishing device in flight.

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ОСИГУРЯВАНЕ НА БЕЗОПАСНОСТ НА ХЕЛИКОПТЕР С ВЪНШНО ПОЖАРОГАСИТЕЛНО УСТРОЙСТВО ЗА ГАСЕНЕ НА ПОЖАР ПРИ ЕКСТРЕМАЛНИ МЕТЕОРОЛОГИЧНИ УСЛОВИЯ В ПОЛЕТ

Н. Загорски

Резюме

В настоящата статия са изследвани и са предложени способи за стабилизация на външното пожарогасително устройство на основата на изследване на механизма за възникване на колебания на външното устройство и на математическо описание на динамика на движение на системата „Хеликоптер–външно пожарогасително устройство", състоящи се в синхронизация на движението на хеликоптера и на външното устройство в полет и създаване на въртеливо движение на устройството около вертикалната ос, съвпадаща с централния кабел за закачване към хеликоптера.