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WATER CAPSULE FLIGHT – A THEORETICAL ANALYSIS, EXPERIMENTAL SETUP AND EXPERIMENTAL VERIFICATION

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Abstract

A bag filled with water is an excellent source of explosion-produced water spray which can be used for extinguishing large fires or for other purposes. The paper presents theoretical models of flight of a bag filled with water, dropped from an aircraft moving horizontally. Results of numerical computations based on this model are compared with results of measurements for the trajectory of a bag dropped from a helicopter. A description of the experimental and numerical setup for this experiment are also discussed.

Keywords: drag influenced flight, water aerosol production.

1. Introduction

The models and experiments described in this paper are of importance for working-out a high-precision method of delivering, to a given point on the ground, a water capsule serving as a source of explosion-produced water spray. It is a part of the work whose final objective consists in developing a water-spray based system of extinguishing and preventing large-scale fires (forest fires, oil plant fires *etc*.), when classical methods of fire damping are of limited use [1,2]. The efficiency of water-spray in extinguishing fires can be very high, provided the spray cloud is produced at the points it is actually needed at. Working-out such a method requires using good theoretical models, reforging them into practically usable algorithms, writing efficient numerical procedures allowing to compute a trajectory quickly and precisely, and, finally, verifying their efficiency in experiments.

The purpose of research discussed in this paper is to develop theoretical models of a capsule flight under the influence of drag in the air, to produce numerical procedures of computing its trajectory and to work out techniques allowing one to measure parameters and reconstruct the shape of the capsule's trajectory to verify the models. The task of hitting a designed point for the purpose of extinguishing a fire required building up a system of high-accuracy localization of the helicopter, guiding it to the appropriate point, choosing the optimal moment for bag release, and initiating the explosion at the optimum height over the target.

2. Assumptions and research methodology

In principle the problem of delivering a water capsule to a given point on the ground is very similar to the problem of hitting a surface target by a bomber with an unguided bomb. There are, however, two problems that make difficult the direct application of the procedures used in military difficult. The first problem follows from the fact that such procedures, as the majority of procedures used by the military, are either classified as a whole or comprise classified crucial components. The second problem is connected with much higher safety standards that must be observed in the case of placing a water-capsule "on target". It seems then more reasonable to develop procedures from the very beginning than to try to adopt non-classified components of similar military procedures.

The ultimate objective consists in developing a high precision system of delivering a water-capsule by an aircraft (presumably a helicopter) a water-capsule to a defined point where it should be exploded in order to generate a cloud of water-spray the playing role of a fire-extinguishing agent. The scheme of such procedure is shown in Fig. 1.

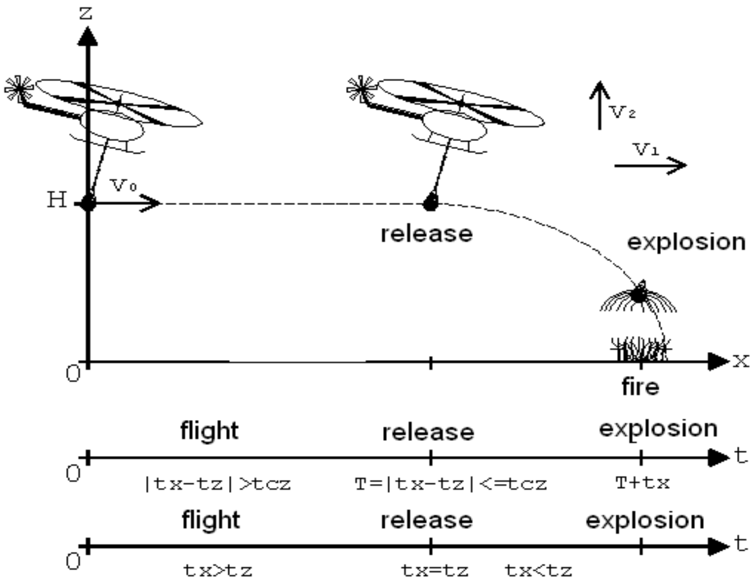

Fig. 1. Schematic view of the procedure of delivering a water-capsule to a designed point.

The Design of a suitable system must be based on theoretical models that can serve as a foundation of numerical programs. The models are founded on the assumption that the water-capsule moves in the air under the influence of a constant and vertical gravitational force and of the Bernoulli drag (pressure drag) that acts against its motion with respect to the air and is proportional to the square of the velocity of this motion. After denoting the velocity by $\vec{v}$, one can write the following formula for the drag force.

$$\vec{Q} = -\frac{c\rho A}{2} v\vec{v} , \tag{1}$$

where

$$v = |\vec{v}| = \sqrt{v_1^2 + v_2^2} ,$$

c is the drag coefficient depending on the shape of the moving body, ρ denotes the density of air and A is the frontal cross-section of the body.

2.1. Equations describing the flight of a water capsule

A water capsule dropped from a horizontally moving aircraft (*e.g.* helicopter) falls down under the composite action of the drag force that has both vertical and horizontal components and the gravitational force that acts all-time vertically. Introducing Cartesian coordinates: the horizontal one x_1 and the vertical one x_2, one can write the equations of motion in the form

$$\dot{v}_1 = -\frac{c_1 \rho A_1}{2M}\sqrt{v_1^2 + v_2^2}\, v_1 \qquad \dot{v}_2 = -\frac{c_2 \rho A_2}{2M}\sqrt{v_1^2 + v_2^2}\, v_2 - g\,, \tag{2}$$

where v_1 and v_2 are the horizontal and vertical coordinates of the capsule's velocity respectively, M is its mass and g denotes gravitational acceleration.

One has to do with a set of ordinary, first order, nonlinear differential equation with respect to the Cartesian coordinates of capsule's velocity. Having these equations solved, one can obtain coordinates of the capsule by simple integration coordinates of velocity with respect to time. Unfortunately, the equations (2) cannot be solved analytically without far-going simplifications. It is so due to the coupling square root term. As such, one has to apply numerical methods for solving the equations.

2.2. Numerical solutions

In this case the standard fourth order Runge-Kutta method [3, 4] was used, and numerical computations were performed in the MATLAB environment. In practice some additional work had to be done, aimed *e.g.*, on optimization of the length of the step of integration, had to be done, but we will not go into technical details.

The solution is obtained for standard initial conditions given by the equations

$$v_1(0) = v_0\ ,\ v_2(0) = 0\,, \tag{3}$$

which corresponds to horizontal motion of the water-capsule at the moment of release. Provided the value of the drag coefficient c is known, one can obtain both components of capsule's velocity as functions of time. Since the main objective consists in computing the trajectory of the capsule, one has to compute its horizontal and vertical components using integrals

$$x_1(t) = \int_0^t v_1(\tau)d\tau + x_1(0)\,, \tag{4a}$$

$$x_2(t) = \int_0^t v_2(\tau)d\tau + x_2(0)\,, \tag{4b}$$

that, in general, have to be computed numerically since the functional forms of v_1 and v_2 with respect to time are not known.

The numerical solution of equations for the components v_1 and v_2 of the capsule's velocity has one more advantage. After some modifications such a procedure can be applied to the problem of flight in the air moving with respect to the ground. In fact, equations (2) describe velocity of the capsule with respect to the ground under the assumption that the air is still. If, however, velocities of wind and that of ascending or descending current are considerable, the equations have to be modified

$$\dot{v}_1 = -\frac{c_1 \rho A_1}{2M}\sqrt{\tilde{v}_1^2 + \tilde{v}_2^2}\,\tilde{v}_1\,,$$

$$\dot{v}_2 = -\frac{c_2 \rho A_2}{2M}\sqrt{\tilde{v}_1^2 + \tilde{v}_2^2}\,\tilde{v}_2 - g\,, \tag{5}$$

where

$$\tilde{v}_k = v_k - V_k\,,\ k = 1{,}2 \tag{6}$$

are coordinates of the capsule's velocity with respect to the air; V_1 denotes the velocity of wind and V_2 the velocity of the vertical current (further generalization, we will not discuss here, would be taking into account the fact that strong and random winds make the problem 3-dimensional instead of 2-dimensional planar problem of flight in still air).

A numerical solution of the equation of motion requires inserting numerical data from the very beginning. Some of them, like the mass M of the capsule or the density of the air ρ are at hand, but the drag coefficients $k_1=cA_1$ and $k_2=cA_2$, appearing in Eqs. (2) and (5) have to be determined from experimental data.

2.3. Computer system for dropping a capsule and reconstruction of a real trajectory

A series of tests consisting in dropping a bag from a horizontally-flying helicopter served two purposes. They were designed to both extracting data allowing one to estimate drag coefficients appearing in equations of motion, and to compare trajectories reconstructed from the videos registered during the actual flights with those obtained numerically for the values of parameters identical with those for the flight (horizontal velocity of the helicopter), and the height of the capsule over the ground at the moment of the release of the latter.

Trajectories of capsules dropped from a helicopter have been reconstructed from a set of frames obtained with a fast video-camera Photron Ultima 1024 (registering pictures of the falling capsule at 250 fps) and a standard (high-resolution video-camera HDV Sony HDR FX1E). The cameras were located at a considerable distance and their optical axis was close to perpendicular with respect to the plane of trajectory. Thus the parallax error was made as small as possible.

As was mentioned before, the computer control system should allow to initiate the explosion of a water bag at an optimum moment and height over the burning material. It has to secure:

- communication with the measuring equipment (serving for determination of the helicopter velocity and position of the bag with respect to the source of fire to be quenched),
- transmission of the flight parameters to the commanding center and reception of information necessary for carrying out the fire-extinguishing action,
- processing the received information according to a suitable algorithm,
- sending a signal causing the release of the water-bag,
- sending information to the initiator about the optimum time delay of the explosion time with respect to the moment of release.

Components of the system must exhibit high reliability irrespective of the external conditions and secure efficient and safe servicing. The core of the system is formed by a controlling computer located on a board of the helicopter. In this role we use a National Instruments-built specialized controller Compact RIO (Fig. 2) equipped with a 400 MHz 32-bit processor, FGPA programmable system and communication modules with serial ports and digital I/O-s. The controller is immune to large electromagnetic and mechanical perturbations and works well in a broad range of temperature and humidity of the air.

Fig. 2. CompactRIO controller.

The multiple threads application of the controlling computer has been developed in the LabVIEW environment and works in the real-time regime [5].

Communication between various components is carried by serial ports or Ethernet. The GPS receiver provides real-time data of the position and velocity in the form of the NMEA (National Marine Electronics Association) strings. The communication microcomputer MOXA coupled to a radio-modem allows receiving important information (e.g. target's coordinates) from the commanding center and sending data on the flight parameters. The controlling computer determines the water-bag trajectory using the Runge-Kutta method. The computed value of the optimum delay-time for the explosion is transmitted to the programmable exploder. All important pieces of information on the present status of the applications are displayed at the pilot's control panel (TPC - 2106T). The scheme of connections between components of the systems is shown in Fig. 3.

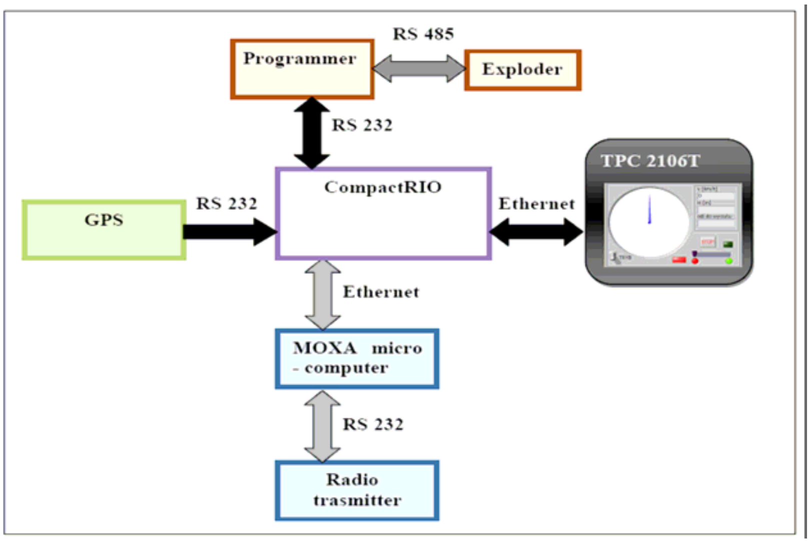

Fig. 3. Components of the water-bag delivery system – the helicopter on-board post: CompactRIO 9014 controller, GPS receiver GX1230GG with RX1210T controller, MOXA UC 7408 LX Plus – mini-computer with the touch panel TPC - 2106T, radio-modem Satelline 3AS 869.

The ground post is equipped with a GPS receiver and a command system server (Fig. 4). The GPS receiver located at a point of known coordinates serves as the base (reference) station which determines the position error, and transmits via a coupled radio-modem a suitable correction to the receiver located at the board of the helicopter. This correction allows to achieve an accuracy of 1cm in the GPS RTK measurement (real time difference dGPS measurement) [6]. The server of the EMP-350 Portable system installed in the moving command center is used for preparing and storing data. It is also used as the control post for the commander of the procedure of releasing and exploding the water-bag. The server is coupled with the on-board computer via the communication microcomputer MOXA and radio-modem.

The database was created using the popular and easily available database engine PostgreSQL. The access to the tables and structures of the database describing applications is achieved with the pgAdmin III tools. The server stores all flight parameters for future processing. Backup data is of importance for development of the system and for carrying on technical and scientific analyses.

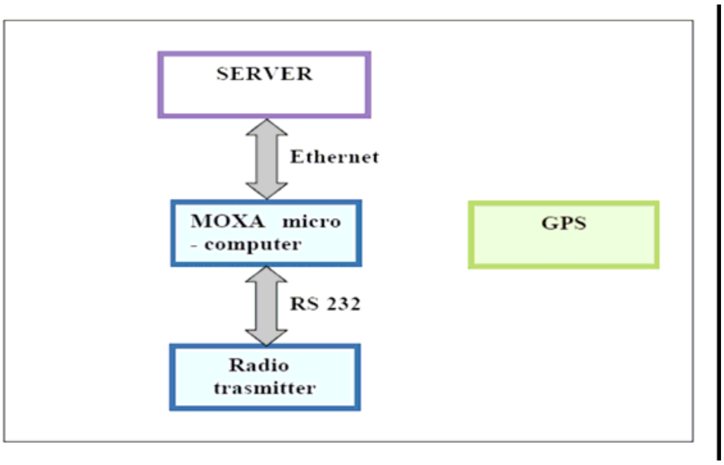

Fig. 4. Components of the water-bag delivery system – the ground post: MOXA UC 7408 LX Plus, ACME type EMP-350 Portable server, GX1230GG receiver with RX1210T controller, radio-modem Satelline 3AS 869.

3. Experimental results

The objective of the experimental tests consisted in comparing trajectories reconstructed from the recorded video frames with those computed for the corresponding values of flight parameters, i.e., the height of the capsule above the ground and its horizontal velocity.

3.1. Comparison of the computed and actual trajectories

Analysis of the capsule's flight is based on equations (5) and their approximate counterparts for identical initial conditions. Simulations of the flight were performed for various values of the following parameters: the drag coefficients k_1 and k_2, the horizontal (v_1) and vertical (v_2) current velocities, the capsule mass m, the release height H, the initial velocity v_0. Computations were carried out using MATLAB procedures based on the Runge-Kutta algorithm of order 2 and 3 (*ode23*) and of order 4 i 5 (*ode45*). In a comparison of the theoretical model with parameters of the actual trajectories, the equality k_1=k_2 was assumed and the common drag coefficient was denoted k.

The helicopter tests allowed to determine values of the drag coefficient k and flight trajectories for a large number of the bag drops. The drag coefficient dependence on the mean drop velocity v fitted to the experimental data is shown in Fig. 5.

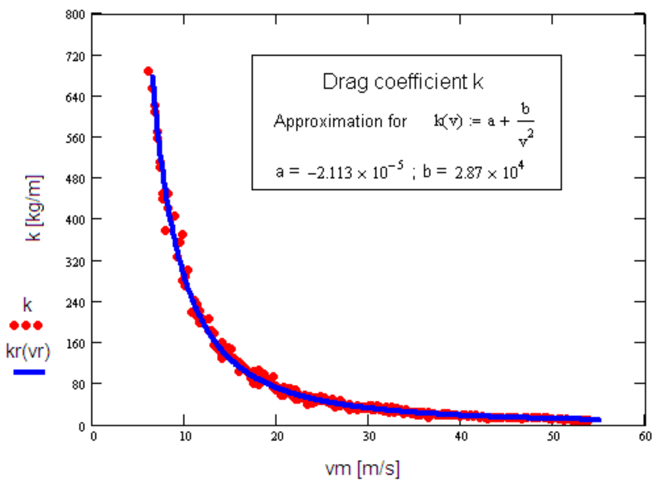

Fig. 5. An approximation of the drag coefficient k(v) vs mean drop velocity for a number of helicopter tests.

It follows from Fig. 2 that one obtains the best fit using an inverse power regression.

The obtained dependence allowed to insert suitable values of the drag coefficient k into the algorithm solving equations of motion (5) and to obtain a model trajectory of the capsule's flight after being dropped from a helicopter moving at a particular height and with a particular horizontal velocity. The model trajectory was then compared with the actual trajectory represented by a number of positions of the capsule registered with a fast video-camera.

The analysis of data registered with the video-camera was performed using the program VIANA (Automatise VIdeoANALyse 3.64 ohneLog, autor Thomas Kersting – Universität Essen, Didaktik der Physik). Results of such a comparison are shown in Fig. 6.

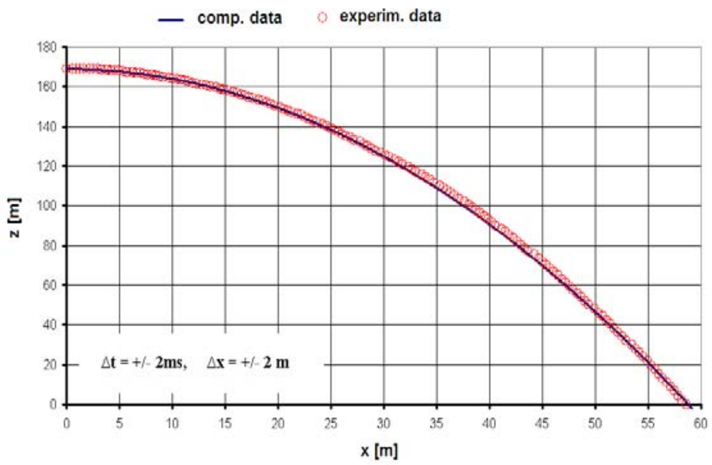

Fig. 6. Comparison of the registered and computed trajectories for one of the tests.
As is clearly visible, the agreement between the actual trajectory and the computed trajectory is more than satisfactory.

3.2. Testing the accuracy of water-bag delivery to a mark

The second series of tests was aimed at the verification of the correctness of the algorithm used for computing the moment of releasing the water-bag, and hitting the mark. Coordinates of the mark – corresponding to the fire focus and the mass of the water-bag were transmitted via the server to the on-board computer at the beginning of each flight. The bag was activated manually by the pilot. Altogether data from 10 flights have been registered by the measuring equipment.

The measured geographical coordinates of the hitting points of the water-bags were used to produce a map of the distribution of the accuracy (Fig. 7). After taking into account the approach angle all hits were within 5 m from the mark, except for the hit in the case of Flight No. 3. In this case, probably a considerable deformation of the bag might influence drag coefficients.

It means that the theoretical model and the numerical algorithm based on it, when experimentally determined values of the drag coefficients are used, allow one to compute with high accuracy the shape of the trajectory of the falling capsule with high accuracy, and if the height of the capsule over the ground at the moment of release is precisely known, the position of the contact of the capsule with the ground can be obtained with an accuracy of the order of a meter or two.

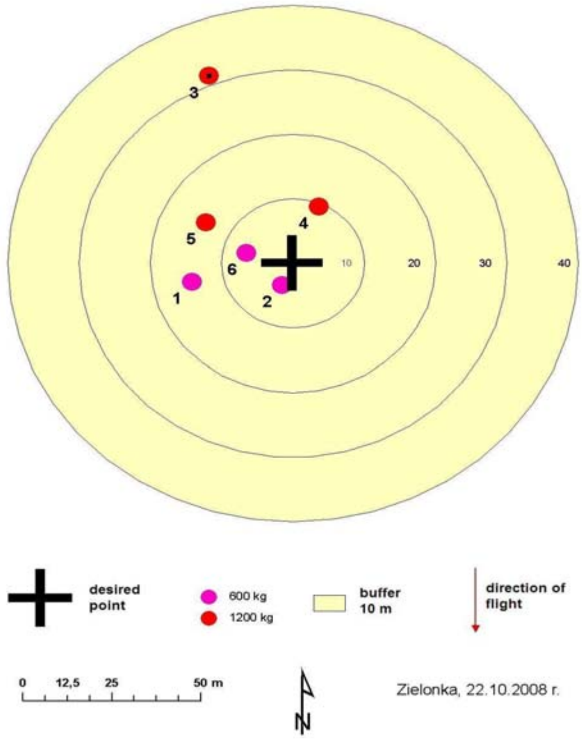

Fig. 7. Results of a series of tests for mark-hitting accuracy.

4. Conclusions

As was mentioned in the introduction, the problem discussed in the present paper is closely related to the problem of dropping an unguided bomb by an aircraft. On the other hand, the problem of high-precision delivery of an object dropped from a moving aircraft to a given point on the ground until to now seemed to be of little importance in civilian applications. Therefore a direct comparison of the obtained results with those obtained by others is a difficult matter because the majority of work on similar subjects is classified as being applicable for military purposes.

The results of the experimental results presented in this paper allow one to draw the following conclusions. The theoretical model of the flight of a water capsule under the drag and gravitational forces, when applied for numerical computations of trajectories of the flight turns out to be very accurate. After supplementing with supporting systems like the capsule height measuring system *etc.* one will be able to compute the desired release point of the capsule almost instantly, thus assuring that the capsule will be delivered to and exploded at the optimal point for maximum efficiency of the produced water-spray cloud, at least in the case of weak winds and vertical currents.

Further research will focus not only on developing such a supporting system but also on generalization of the model and numerical programs derived from it as well as of the technique of recording the flight of the capsule and reconstructing its trajectories, to be able to take into account their non-planar character in the case of flight under the influence of strong wind. That would complete the whole system of delivering a capsule to a selected point in almost all but the roughest atmospheric conditions.

Acknowledgements

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