

ABOUT THE INFLUENCE OF THE ATMOSPHERE OVER THE WILDFIRE ON THE FLIGHT DYNAMICS FOR THE HELICOPTER SIMULATOR APPLICATION

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ABSTRACT

The scope of this paper is modelling of the atmosphere over the wildfire and analysis of its influence on the helicopter flight dynamics in defined conditions. To achieve realistic simulation of helicopter flight over the wild land fire it is required to take into account the influence of the fire on the atmosphere conditions. The work presented here is in the framework of the project of helicopter simulator for Mi-171Sh, a modernized variant of the Mi-8/17 helicopter, which is used in the Croatian Air Force for both military and civil applications, especially for its specific use for the firefighting purposes. The influence of fire atmosphere environment on rotor aerodynamics and the whole aircraft flight dynamics can be significant. For the flight training device the results for the spread of the fire are not required, but it is necessary to calculate the aerodynamic forces and moments using density and wind in the atmosphere influenced by wildfire. This aerodynamic calculation is applied with many hypotheses. Presented work is oriented to the determination of the influence of the atmosphere over the wildfire on the helicopter performances under the same hypotheses. Because of this reason we are looking for the atmosphere model under the same hypotheses as for the aerodynamic calculation and only problems relevant to the evaluation of the aerodynamic forces and moments will be taken into account. For the investigation of the specific effects it is required to have reliable mathematical models both of the wildfire and helicopter. Aerodynamic model of the rotor based on the blade element theory is analysed with presented model of atmosphere model over the wildfire. Results of influence of atmosphere over the wildfire on helicopter required power in forward flight and available power are also presented. For these analyses a generic example helicopter similar to Mi-8/17 has been used. Visualization aspects of fire and smoke atmosphere for the helicopter simulator project are also covered in the paper. Helicopter data approved by the manufacturer are required for mathematical models of the future simulator what leads to a successful certification process both for military and civil operational use. Although there are already present several different simulators for this type of helicopter, specifics of this project are fulfilments of the requirements for the development for the training for the missions with external load, aerial firefighting, search-and-rescue operations with landings in near-fire areas etc.

1. INTRODUCTION

Development of multifunctional tactical simulators and training systems is extremely important to enhance and improve the quality, but also for reducing the cost of training. For these reasons, stronger trend of the implementation of various simulation devices and training systems in the process of training of the helicopter crews is present. With development of capabilities of the modern computer systems and technologies, especially those

of distributed interactive modelling and simulation and more sophisticated mathematical models of the future generation of simulation devices, it will be possible to achieve high fidelity of helicopter flight simulation. According to Feasibility Study for the Mi-171Sh Helicopter Simulator, with modern training systems various flight and tactical tasks can be modelled from 80 to almost 90 percent. Moreover, their use reduces the cost of training is 20-30 percent,

while reducing the time of use of real helicopters for 40-70 percent. The quality of education and training of helicopter crew is particularly important in specific applications such as firefighting from the air. Thereby, training for this type of missions includes a complex tasks such as flight with external slung load (water bucket), unplanned and planned landing on unprepared terrain, training procedures with engine malfunction and similar. All of these tasks are under the special conditions of the atmosphere prevailing in the zone of wildfire. For the purpose of helicopter crew training in the complex missions like firefighting there are two main requirements on the helicopter flight model that should be considered - operating the helicopter with external slung load and atmosphere conditions influenced by the fire. Training of helicopter external load operations is important for the pilot and crew readiness to deal with the real-world situations during aerial firefighting. For realistic simulation of external load it is necessary to analyse dynamics of the load, which is coupled with the dynamics of the helicopter. Problem of the dynamics of the helicopter with slung load (water bucket) can be classified as the multibody dynamics problem with two rigid bodies with cable links presenting the model constraints.

Simplified model of the atmosphere above the fire and the impact of such an atmosphere on the both rotor aerodynamics and dynamics of helicopter flight are included in this paper. A model based on blade element theory is applied for the analysis of thrust and torque of the helicopter main rotor in forward flight. Helicopter required and available power are estimated for horizontal flight in the atmosphere above the wildfire. Both analyses relate to the steady state flight of the helicopter for which a generic example helicopter similar to Mi-8/17 has been used. In addition, implementation in flight simulation, visualization and system requirements that facilitate transfer of acquired skills from the simulator into the real world are discussed. Croatian Air Force is equipped with a Mi-171Sh multi-purpose helicopter and significant component of its application is aerial firefighting with the water bucket system. Flight simulator will be used for helicopter Mi-171Sh training and for retraining the crew with a different type of aircraft as well as for raising and maintaining levels of crew experience levels on helicopter Mi-171Sh. Project of the simulator should be in full compliance with the criteria defined by the standard JAR STD 3H FNTP III MCC. Regarding the price of the helicopter Mi-117Sh compared with prices of other helicopter manufacturers of the same class, it is expected that this helicopter in the future will be one of the most widespread. In this context, is not superfluous to emphasize the fact that high quality training systems and simulators specifically for helicopter Mi-171Sh have increasing importance and role in the future. In the development of simulator for

the Mi-171Sh with high fidelity simulation, it should be emphasized that the quality and usefulness is of a vital and important role that certified mathematical models related to the dynamics and aerodynamics of helicopters and all its subsystems are used.

2. SIMPLIFIED MODEL OF THE ATMOSPHERE OVER THE WILDFIRE

2.1. Introduction

Modelling of forest fire present demanding task and it is highly coupled with the atmosphere [1]: complicated chemistry processes, nonlinear interaction between the fire and airflow, complicated and not fully comprehended radiation and combustion properties. Model given in [1] is a three-dimensional, time dependent wildfire simulation model coupled with atmosphere. Another coupled atmosphere-fire model is analysed in [2].

Interaction between the fire and atmosphere is mainly manifested by wind: wind can be strongly modified or solely produced by fire; and fire spread is highly influenced by wind through advection of hot gases and burning material. This fire-atmosphere coupling can occur over spatial scale from tens of meters at the fire front to kilometres on the scale of overall area affected by fire. Main aspect of application of model [1] is prediction of fire spread and it requires large computer recourses and complex input data like a configuration of terrain with description of fuel (forest, bushes, grass, or other), etc.

For the flight training device results for the fire spread are not relevant, but results for the density and wind in the atmosphere influenced by a wildfire are very important for the determination of aerodynamic forces and moments. This aerodynamic calculation is applied with many hypotheses. Main objective of this paper is determination of influence of the wildfire on the helicopter performances under the same hypotheses. For this reason we are looking for atmosphere model under the same hypotheses as in aerodynamics and we take in account only the problems which are important for evaluation of the aerodynamic forces and moments.

2.2. Assumptions

Cartesian coordinates with z -axis oriented up will be used here. From a reference [3] we have:

equation of continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0, \quad (1a)$$

momentum equation

$$\rho \frac{D\mathbf{V}}{Dt} = -\nabla p + \mathbf{B} + \mu \nabla^2 \mathbf{V}, \quad (1b)$$

energy equation (pp 43, equation 3.55)

$$\rho C_p \frac{DT}{Dt} = \frac{Dp}{Dt} - \nabla(\mathbf{q}_c + \mathbf{q}_r) + q''' + \Phi. \quad (1c)$$

In equations (1):

- \mathbf{q}_c is the flux of heat conduction from the environment to a control volume, determined by Fourier's law $q_c = -\lambda \nabla T$. In this paper the flux of heat conduction from a control volume to the environment is required,
- λ , thermal conductivity is accepted to be a constant,
- \mathbf{q}_r is the radiation heat flux vector, neglected here ([3] pp. 44),
- q''' is the internal heat generation rate per unit volume, doesn't exist here ([3] pp. 44),
- Φ is the dissipation function, neglected here.

Additional suppositions introduced here are:

- turbulence is neglected,
- air is accepted to be a perfect gas ($dU = C_v dT$),
- steady, inviscid, compressible one dimensional flow in direction of z is assumed:

$$\mathbf{V} = [0 \quad 0 \quad w]^T,$$

$$\mathbf{B} = [0 \quad 0 \quad -\rho g]^T,$$

$$\frac{D}{Dt} = w \frac{d}{dz}.$$

For these conditions equations (1) have following form:

equation of continuity

$$\frac{d(\rho w)}{dz} = 0, \quad (2a)$$

momentum equation

$$\rho \frac{dw}{dz} w = -\frac{dp}{dz} - \rho g, \quad (2b)$$

energy equation for the air as a perfect gas ($dU = C_v dT$)

$$\rho C_p \left(w \frac{dT}{dz} \right) = \frac{dp}{dz} w - \lambda \frac{d^2 T}{dz^2}, \quad (2c)$$

equation of the state

$$p = \rho R T.$$

R is a gas constant of the humid air as we use it in the flight mechanics [4].

We have four equations for four functions of altitude z : pressure $p(z)$, density $\rho(z)$, temperature $T(z)$ and vertical wind $w(z)$. A first and second equation are differential equations of the first order and third equation is of second order. In order to solve equations numerically four initial conditions are required: T_0, T_0', w_0, p_0 for $z = 0$.

2.3. Transformation of the Equations

Continuity equation (2a) can be given in following form

$$\rho w = C.$$

With the introduction of new variable G :

$$\frac{dT}{dz} = G$$

and for given C_p specific heat at constant pressure and C_v specific heat with $C_p - C_v = R$, we finally have three differential equations and two algebraic equations for p, ρ, w, T, G as a functions of z :

$$\frac{d\rho}{dz} = \rho \frac{g + RG}{w^2 - RT} \quad (3a)$$

$$\frac{\lambda}{C} \frac{dG}{dz} = -RT \frac{g + RG}{RT - w^2} - C_v G \quad (3b)$$

$$\frac{dT}{dz} = G \quad (3c)$$

$$\rho w = C \quad (3d)$$

$$p = \rho R T. \quad (3e)$$

2.4. Analytical Approach

2.4.1. Gradient of a Temperature

In the equation (3b) w^2 term can be neglected in comparison to the term RT so differential equation for $G(z)$ would have following form:

$$\frac{dG}{G + \frac{g}{C_p}} = -\frac{C_p C}{\lambda} dz. \quad (4)$$

With the initial condition $z = 0; G = G_0$ the solution of (4) is:

$$G = \left(G_0 + \frac{g}{C_p} \right) e^{-(C_p C / \lambda) z} - \frac{g}{C_p}. \quad (5)$$

In the case of standard atmosphere $C = 0$ for all altitudes z equation (5) becomes $G = G_0$.

2.4.2. Temperature

With relation (5) for the function $G(z)$ the differential equation of the temperature (3c) becomes:

$$\frac{dT}{dz} = \left(G_0 + \frac{g}{C_p} \right) e^{-(C_p C / \lambda) z} - \frac{g}{C_p}. \quad (6)$$

For initial condition $z = 0 \rightarrow T = T_0$ solution of (6) is:

$$T = T_0 - \frac{\lambda}{C_p C} \left(G_0 + \frac{g}{C_p} \right) \left(e^{-(C_p C / \lambda) z} - 1 \right) - \frac{g}{C_p} z, \quad (7)$$

or with the function $G(z)$ from (5):

$$T = T_0 - \frac{\lambda}{C_p C} (G - G_0) - \frac{g}{C_p} z. \quad (8)$$

2.4.3. Density

The density is given by differential equation (3a). As mentioned earlier term w^2 can be neglected compared to term RT to get:

$$\frac{d\rho}{\rho} + \frac{dT}{T} = -\frac{g}{R} \frac{dz}{T}. \quad (9)$$

After integration of (9) for $z = 0 \rightarrow T = T_0$ and $\rho = \rho_0$ it follows that:

$$\ln \left(\frac{\rho T}{\rho_0 T_0} \right) = -\frac{g}{R} \int_0^z \frac{dz}{T},$$

and with the state equation the pressure is given with:

$$p = p_0 e^{\left(-\frac{g}{R} \int_0^z \frac{dz}{T} \right)}. \quad (10)$$

This is well known equation for the pressure in the standard atmosphere. So this equation is also useful in this case.

2.5. Results

Numerical implementation of the differential-algebraic equations (3) with described initial conditions gave identical results as the analytical

equations (8,10) for the same conditions. Numerical model of (3) showed high numerical sensitivity on the value of parameter C . For analytical model in equation (8) this problem is obvious for $C = 0$.

Due to the described numerical sensitivity of the model on the value of C the equation (3d) for vertical velocity w could not be utilized.

Initial conditions for temperature could be presented as:

$$T_0 = T_{0,s} + \Delta T,$$

with ΔT as temperature difference or temperature anomaly from the $T_{0,s}$ standard temperature at sea level ($z = 0$). Temperature anomaly ΔT for a wildfire could range from 50 K up to 500 K or even more, depending on the fire fuel, distance from the fire front or on terrain configuration [1]. Initial value p_0 for the pressure is assumed to be equal to standard value for $z = 0$.

The equation for a G temperature gradient according to equation (5) shows that very quickly (after several meters) first term disappears and temperature gradient is equal to second term:

$$G = -\frac{g}{C_p}. \quad (11)$$

For temperature anomaly $\Delta T = 50$ K this gradient would be $G = -0.00958$. Initial value of temperature gradient $T_0' = G_0$ is chosen according to equation (11).

It is well known from the standard atmosphere that this gradient has to be equal to -0.0065. We believe that in this model the temperature decreases faster because we didn't take into account the radiation of the sun. It means that the small vertical wind w doesn't influence significantly the temperature, density and pressure.

Results of the presented simplified model of atmosphere over the wildfire are given on Fig. 1 and Fig. 2. Results of the model were expected. The high temperature strongly influences density (Fig. 2), higher temperature anomaly causes smaller values of density. The decrease of density changes very slowly with altitude as well as the temperature (Fig. 1). For given initial conditions pressure variation with altitude is almost identical to its variation for standard atmosphere.

Vertical wind w can not be determined with presented simplified model vertical wind while results of coupled fire-atmosphere model [1] for vertical wind are up to 20 m/s on altitudes up to 1000 m. The difference between the results for vertical wind can also explain the difference of the results for the temperature gradient between the presented model and fire-atmosphere model [1].

3. INFLUENCE OF ATMOSPHERE OVER THE WILDFIRE ON FLIGHT DYNAMICS

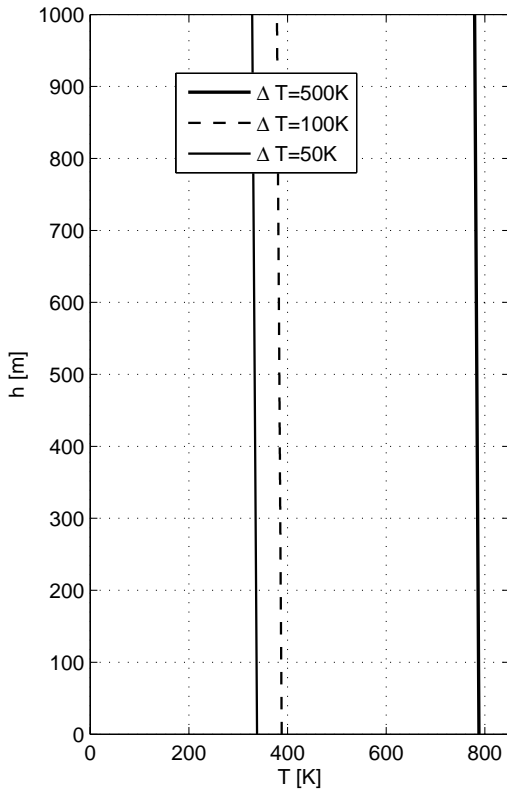


Fig. 1. Results for temperature T with variation of the altitude z for different values of temperature anomaly ΔT

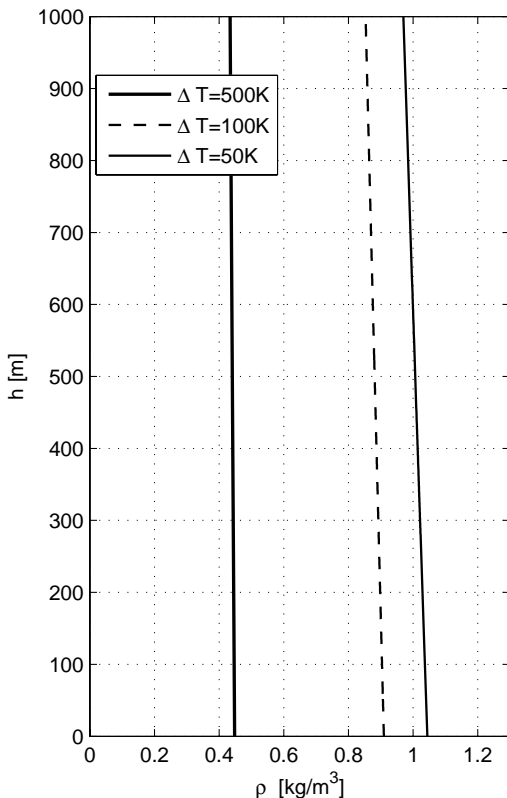


Fig. 2. Results for density ρ with variation of the altitude z for different values of temperature anomaly ΔT

Primary influence of the presented model of atmosphere on the helicopter is the value of density (Fig.2). Decrease of the density value has direct consequence on all aerodynamic forces and moments of the helicopter. Furthermore, it also significantly affects the performance of the engine.

Since the presented one-dimensional model of atmosphere over a wildfire is not time dependent it will be applied here only for determination of its influence on the helicopter in steady state flight.

Following [1] the values of vertical wind in atmosphere over the wildfire can be significant. The vertical wind presents a vertical gust and it is another important influence of atmosphere over the wildfire on the helicopter flight dynamics. Since the vertical wind can not be determined with presented simplified model its influence on helicopter dynamic will not be analysed in this paper.

3.1. Aerodynamic Model

Results of the simplified model of atmosphere over the wildfire are implemented in the aerodynamic model of the rotor based on the blade element theory [5]. The influence of the temperature anomaly ΔT was analysed on the main rotor of the example generic helicopter similar to the Mi-8/17. Results for thrust coefficient C_T and power coefficient C_P in dependence of advance ratio μ are given on Fig.3 and Fig.4. Results for thrust T and torque Q in dependence of temperature anomaly and advance ratio are presented on Fig. 5. and Fig. 6.

For this analysis trim values of collective and cyclic pitch angle as well as coning and cyclic flapping angle for standard temperature were applied for all values of temperature anomaly. Following the presented results the pilot would have to apply new values of pitch control in order to preserve overall equilibrium of the aircraft.

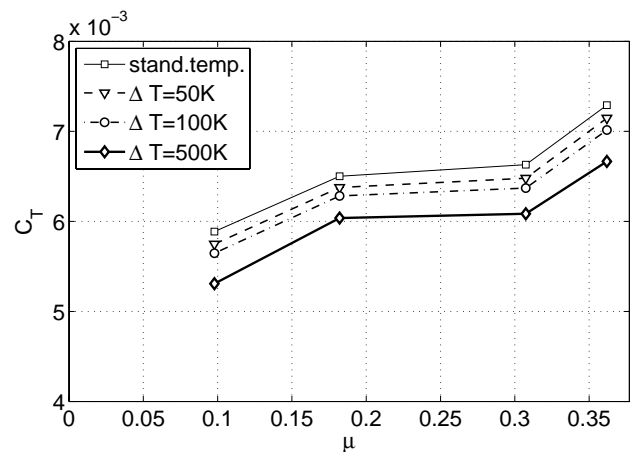


Fig. 3. Thrust coefficient C_T in dependence of temperature anomaly ΔT and advance ratio μ

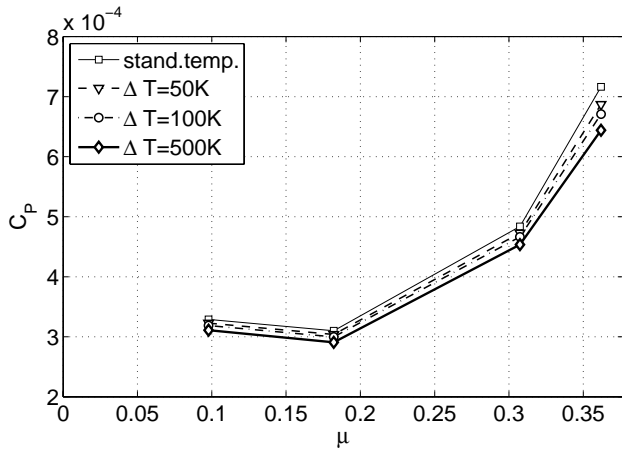


Fig. 4. Power coefficient C_p in dependence of temperature anomaly ΔT and advance ratio μ

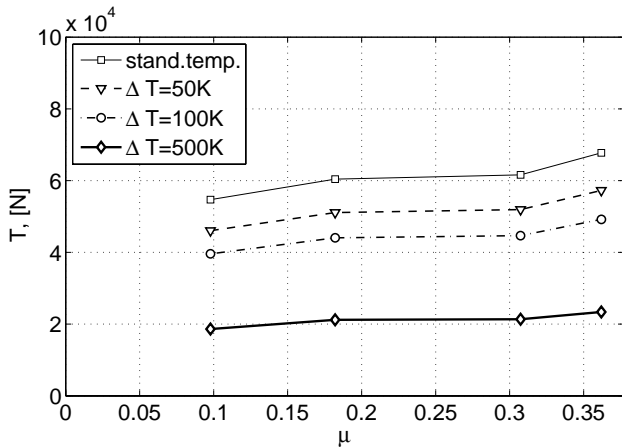


Fig. 5. Thrust T in dependence of temperature anomaly ΔT and advance ratio μ

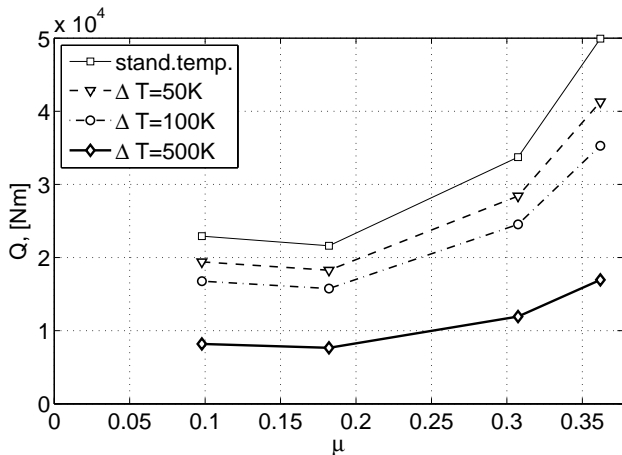


Fig. 6. Torque Q in dependence of temperature anomaly ΔT and advance ratio μ

3.2. Required and Available Power

For the same example generic helicopter a simple analysis of the required power was conducted. In this analysis uniform inflow is assumed and empirical correction for induced and profile power [6,7] was applied for helicopter in horizontal flight at altitude $z = 500$ m. Required power includes also estimate

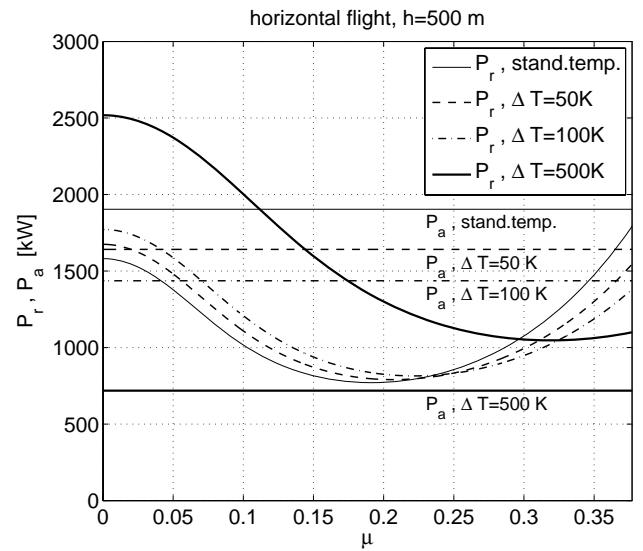


Fig. 7. Required P_r and available power P_a for example helicopter, as a function of advance ratio μ and temperature anomaly ΔT .

of parasitic power, tail rotor power and transmission and accessories power. Presented simplified model of atmosphere over a wildfire was applied with variation of the temperature anomaly ΔT . Results of this analysis for the required power P_r as a function of advance ratio μ are presented on Fig. 7.

It can be noted that for hover and for smaller advance ratios required power is higher for higher values of temperature anomaly in comparison to the power required for standard atmosphere. This is due to the significant rise of induced power required for the aircraft to retain level flight. For higher values of advance ratio required power is smaller in comparison to the power required in standard atmosphere mainly due to the drop of parasitic drag of the helicopter as a result of smaller values of density.

Results for available power P_a of two turboshaft engines of example generic helicopter are also presented on Fig. 7. It is assumed that power available from the turboshaft engine is constant with airspeed and a function of pressure and temperature ratio [7]. Rise of temperature anomaly and decrease of density according to the results of simplified model of atmosphere over the wildfire results in drop of available power. The presented results for required and available power causes drop of helicopter excess power in horizontal flight and restriction of helicopter flight envelope. Therefore, moderate advance ratios (for minimal required power in standard atmosphere of even higher) can be recommended for flight of the analysed helicopter over the wildfire.

Presented results for required and available power can be presented as the effect of density altitude: rise of the temperature anomaly over the wildfire follows a rise of density altitude.

4. VISUALIZATION OF ATMOSPHERE OVER THE WILDFIRE IN FLIGHT SIMULATION

When visualizing the wildfire simulation it is desirable for the results to look as realistic as possible without compromising accuracy. The purpose of wildfire and smoke visualization modelling is to gain a realistic display of fire and its effects on atmosphere above the wildfire. Such models [8] predict smoke and/or hot air flow movement caused by fire, wind, ventilation systems and other factors by solving numerically the fundamental equations governing fluid flow (Navier-Stokes equations). Furthermore, this models [8] uses large eddy simulation (LES) to predict the thermal conditions resulting from a fire. The fire itself is a source term in the governing equations, creating buoyant motion that drives the smoke and hot gases throughout the simulation. According to [8], one of the biggest challenges in visualizing wildfire dynamics and smoke is how to convert the multi-dimensional data generated by a wildfire model into a form that can be easily understood. Fire data can easily have five or more dimensions. For example, to display time dependent scalar data would require five dimensions: three spatial dimensions to visualize position, one time dimension and one dimension to visualize the variable of interest. Time dependent vector quantities require eight dimensions to display: three spatial dimensions, one time dimension, one dimension to visualize the variable as before plus three additional dimensions to display the flow direction and speed. A major challenge to effective visualization is that the computer screen has only two dimensions to display these data. Volume rendering is ideal for modelling the fire and smoke because of its ability to directly represent objects with transparency and light-emitting properties. It is important to note that the simulation and the resulting visualization are not directly modelling flames or smoke; they are derived from the temperature data generated by simulation [9].

Training of external load operations, such as firefighting purposes, places additional visualization and system requirements in comparison with typical helicopter flight simulation, related to the external load and a variety of external load training scenarios. Visualization, like external load modelling, focuses in greatest detail on aspects of the real world that are salient to the success of training in the simulator. Namely, present complexity of development of photorealistic real-time visualization indicates that setting perfect photorealism as a goal in the simulator may not be sensible from the return-on-investment perspective.

For basic training of the external load operations, visualization subsystem includes a database of typical 3D models of objects in the virtual scene: a virtual terrain, helicopter, a simple type of an external load

and the corresponding sling. Most of these 3D models are also important for the visualization to the pilot. The difference is in the position of the viewpoints of the pilot (cockpit) and the load-supervising crew member (middle of the helicopter floor or side door). The load-supervising crew member needs to be able to estimate distances correctly in the simulator, as distance estimation is an important part of the real-world external load operations. Therefore, the visualization needs to support the most important properties of the human vision and account for the properties of the real world that enable good distance estimation when operating an external load. Shadows of the load, the helicopter and the surrounding objects are important source of information regarding the height of the load [10]. Additionally, terrain coverage by shadows is important for assessment of the best approach direction for the helicopter, together with information regarding terrain configuration, objects on the terrain, wind direction and sun position [11]. Moreover, shadows assist in better relative distance estimation of objects in virtual scenes [12] and present an indicator for distance estimation complementary to the stereo vision. Therefore, the simulator needs to include algorithms for real-time shadow visualization.

Advanced training conditions may impose additional requirements depending on the exact conditions: training in confined area with obstacles; training with various load types; training under decreased visibility from interaction of the helicopter blade air wave with the terrain surface, like dust, sand, or water; training under atmospheric conditions that complicate external load operations, like wind, fog, rain etc.; training in night conditions, and so on.

5. CONCLUSION

In this paper a simplified one-dimensional steady model of atmosphere over the wildfire is presented. This model is applied in analysis of the influence of atmosphere over the wildfire on the helicopter main rotor aerodynamics, total required and available power. Main effect of the simplified atmosphere model is decrease of density with the rise of temperature anomaly from the standard atmosphere temperature. Vertical wind is another result of atmosphere model over the wildfire that can be significant for helicopter dynamics but it can not be determined with presented model.

With decrease of the density there is a real danger of insufficient lift force. For the simulator application it is necessary to estimate how density of air is changing when the helicopter is approaching wildfire site and how it changes with height above the wildfire. Presented simplified model can be applied

in mathematical model of helicopter simulator but initial values for temperature anomaly at the surface are required.

The presented model is expectedly unable to fully describe time-dependent atmosphere coupled with fire as in [1]. Main disadvantage of presented model are unrealistic results for vertical wind. Simulation results of coupled fire-atmosphere model [1] shows that strong time-dependent vertical winds are generated (up to 20 m/s at altitude of 1000 m) and that influence of horizontal wind should not be ignored. This means that it is necessary to return to the theoretical level state of the atmosphere above the wildfire and consider the changes over time in horizontal and vertical direction with influence of the wind. Furthermore, model can be improved with heat convection vertical flow included.

An important operational consideration is the effect of altitude on overall helicopter performance. It is shown that effect of density can be treated as the effect of density altitude on required power [7]. Furthermore, effect of an atmosphere influenced by the wildfire on the helicopter engine characteristics should be also investigated. Following simple model of engine power characteristic as described in [7], a higher density altitude will also affect the power available from the engine, resulting in a large decrease of the excess power and reduction of helicopter flight envelope.

For the visualization in helicopter flight simulator fire and its effects have to be considered and the task of realistic visualization model is further complicated with the external load that is common for the operations of firefighting.

Application of the simplified model of the atmosphere over the wildfire for the analysis of main rotor aerodynamics and required and available power could result with several recommendations for the pilot of specific helicopter. There should be a certain reserve of aerodynamic forces from the main rotor in order to keep aircraft in vertical balance, primary a reserve of pitch collective angle. From the reduced helicopter flight envelope in the atmosphere over the wild fire it follows that smaller airspeeds should be avoided. These recommendations can be even more concrete with the application of more detailed and extended model than the presented simplified model of atmosphere over the wildfire.

Future work would enclose improvement of the presented model of the atmosphere over the wildfire and its implementation in the project of Mi-171Sh helicopter flight simulator.

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