Aerospace Science and Technology 64 (2017) 31–38

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Modeling the electrostatic charging of a helicopter during hovering in dusty atmosphere

Holger Grosshans [a,*], Robert-Zoltan Szász [b], Miltiadis V. Papalexandris [a]

[a] *Institute of Mechanics, Materials and Civil Engineering, Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium*
[b] *Division of Fluid Mechanics, Lund University, Box 118, 22100 Lund, Sweden*

ARTICLE INFO

Article history:
Received 17 October 2016
Received in revised form 2 January 2017
Accepted 19 January 2017
Available online 24 January 2017

Keywords:
Particulate flows
Aerospace
Electrostatics
Safety

ABSTRACT

A helicopter flying through an atmosphere containing particulates may accumulate high electrostatic charges which can challenge its operational safety. In this paper we elaborate and validate a triboelectric charging model to predict the electrification experienced by a helicopter while hovering in dusty air. We employed Large Eddy simulations to describe the turbulent structures inherent in the flow around the rotorcraft. The dust particles were tracked individually in a Lagrangian framework. A model accounting for the triboelectric charge transfer when a particle hits the helicopter was introduced. The results demonstrate the accuracy of the proposed approach and allow a detailed analysis of the location of the charge accumulation.

1. Introduction

During flight a helicopter accumulates electrostatic charge on its body. This can be mainly attributed to friction with the surrounding air or to ionized particles in the engine exhaust. However, if the atmosphere contains particulates such as rain, snow, dust, sand or volcanic ash, the charge transfer is significantly enhanced due to triboelectric effects [33].

There is only a limited amount of studies reported dealing with the hazards arising from the electrification of the helicopter structure. Therefore, it is worth mentioning some earlier works related to fixed-wing aircraft which may be, at least to some extend, transferable to rotorcraft. For example, O'Neill [26] discusses that accumulated electrical charge and its discharge can indirectly threaten flight safety through the generation of Radio Frequency Interference (RFI). RFI may disrupt aircraft communication and navigation by increasing equipment ambient noise levels and making reception difficult or impossible. Even worse, the discharge of static electricity can lead to fuel tank explosions. Following the investigations after the loss of the Trans World Airlines Flight 800 over the Atlantic ocean in 1996 [25], it is unlikely that the ignition of flammable vapor in the center wing tank was caused by static electricity. Nonetheless, the accident report stated that the discharge of static electricity had resulted in fuel tank explosions prior to that accident.

A different type of airborne object was considered by Horenstein and Roberts [16] who investigated whether the nylon fabric of parachutes may acquire enough electrostatic charge to impede or even prevent parachute opening. In their study they used Bernoulli's equation to estimate the aerodynamic forces during the early stages of inflation. Further, they combined it with a two-slab model for the electrostatic force exerted by separated regions of charged parachute fabric and compared the results with measurements of a small-scale charged parachute deployed in a wind tunnel. Their findings indicated that electrostatic forces on a parachute charged to $\pm$ 15 $\mu C/m^2$ can prevent parachute opening at air speeds below 4.5 m/s.

During rotorcraft operation, there are additional risks and hazards arising from the build-up of electrostatic charge. While in a fixed-wing aircraft a physical short-circuiting element to ground is very unlikely, the presence of high electrostatic potentials constitute a safety hazard for helicopters since they are frequently operated close to the earth's surface. Those operations, for example external cargo hookups or air–sea rescue, favor the discharge of electric charge in the form of an arc. Seibert [33] reported injury of ground personnel and persons involved in air–sea rescue as well as ignition of fuel slicks in the ocean. Further hazards may be the ignition of air–fuel mixtures over a crash area during a rescue operation or the self-ignition of starters and detonators on externally carried weapon systems [14].

The electrostatic charging of metal helicopters is relatively easy to control through discharging devices [14]. However, the ever-increasing use of composite materials imposes new challenges since those materials are more resistive than aluminum. In order

* Corresponding author.
E-mail address: holger.grosshans@uclouvain.be (H. Grosshans).

http://dx.doi.org/10.1016/j.ast.2017.01.014

to maintain a sufficient lightning strike and static electricity protection, the US authorities require the incorporation of acceptable means of diverting the resulting electrical current so as not to endanger the rotorcraft [7]. These means are commonly metal grids laid in the composite to improve its conductivity. Therefore, to aid the design process there is a need to predict the amounts of expected electrostatic charge. However, there is scarce information available about it in the literature.

A test program documented by Seibert [33] found a maximum voltage accumulation of 200 000 V and a maximum charging current of 50 μA at helicopters flying in the Arctic. These high values were attributed to snow particles which were blown by the downwash towards the rotor blades. However, it was acknowledged that this does very probably not correspond to the maximum voltage and maximum charging current which may be encountered during less favorable weather conditions.

The only numerical study related to the electrification of helicopters that we are aware of is the one of Salmela et al. [30]. Therein, it was assumed that all particle–helicopter impacts take place at the rotor blades. Further, the authors simplified the blade geometry to a circular rod. This results in a generic flow for which empirical correlations are available. They used these correlations to determine the collision probability dependence on the particle Stokes number. According to their calculations, the highest contribution to the charging of the rotor blade is induced by particles of a mass median size of 20 μm. This size is considered representative of the particles that surround a helicopter that releases dust from the ground or from sandy terrain.

An accurate numerical prediction of the electrostatic charging of helicopters would require to resolve the complex coupling between aerodynamics and electrostatics. However, as Vos et al. [40] elaborated in their review article, helicopter aerodynamics is one of the most challenging applications for Computational Fluid Dynamics (CFD). The CFD algorithm is required to account for the blade-vortex interactions and interactions of the wake induced by the main-rotor with the rear fuselage or with the secondary rotor. The numerical grid must be capable of treating surfaces in relative motion, reflect the rotor rotation, its deformation, the aero-elastic coupling and finally the trim of the full aircraft. Thus, advanced meshing techniques are applied which usually involve grid connectivities, mesh reconstruction and local refinements. An example of the prediction of the rotor–fuselage interaction was presented by Boniface et al. [1]. They made use of the Chimera overset technique in which the connectivities between rotating blocks and fixed blocks are time dependent. The progress achieved in mesh generation and CFD algorithms, as well as the growing power and capacity of modern-day computers, encouraged numerical simulations of flows around full-size helicopters. However, due to the complexity of these flows many questions remain open.

On the other hand, the computation of electrostatic charging of flows in simpler geometries such as pneumatic powder transport in pipes has reached a certain level of maturity. Notable implementations include the one of Watano et al. [41] who utilized the availability of analytical velocity profiles for pipe flows. Additionally, Kolniak and Kuczynski [24] and Tanoue et al. [38,39] solved the Reynolds-Averaged Navier–Stokes equations for the turbulent flow of the carrier fluid. Recently, the authors of the present paper employed Large-Eddy Simulations (LES) to compute temporally and spatially resolved numerical results for the charging process in a pipe flow. Further, they implemented dynamic models to account for the particle-pipe and inter-particle charge transfer. By doing so, highly accurate predictions of the powder charge were obtained [9–12].

The aim of the current paper is to present a numerical concept to compute the electrostatic charging of helicopters due to contact with dusty atmosphere. It should be emphasized that it is not scope of the study to provide an accurate representation of the aerodynamics of a helicopter, but rather to accurately predict its electrification. To this end, we employed our previously developed model which is capable of computing the triboelectric charge transfer when a particle hits a solid surface. This model is implemented in a CFD solver for the flow of air around a generic transport helicopter during hovering. In the following we first describe the mathematical model and the set-up of the simulation. In Sec. 4 we discuss the results and then we provide the conclusions of our investigations.

2. Mathematical model

A coupled Eulerian–Lagrangian solver has been developed to describe the dynamics of dust in the atmosphere. Elgobashi [6] proposed that for volume fractions below 10^{-6} the presence of particles would have no effect on turbulence. Since the volume fraction of the dusty atmosphere considered in the present study is below that value, cf. Sec. 3, one-way interaction has been considered between the two phases. This means the particles are transported by the air but they are assumed not to perturb the flow-field itself. The mathematical model used in the study is outlined below.

2.1. Gaseous phase

The continuous gaseous phase is described in Eulerian framework by the Navier–Stokes equations with constant diffusivities. The volume occupied by the solid is negligible compared to the volume occupied by the gas. Thus, the volume fraction of the gaseous phase is assumed to be unity, i.e. the flow is dilute. The mass and momentum balance laws read

$$\nabla \cdot \mathbf{u} = 0 \tag{1a}$$

and

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho_g}\nabla p + \nu_g \nabla^2 \mathbf{u} + \mathbf{F}_s \,, \tag{1b}$$

respectively. In the above equations $\mathbf{u}$, p, ρ_g and ν_g are the gas velocity, pressure, density and kinematic viscosity, respectively. The term $\mathbf{F}_s$ accounts for the presence of a solid object and is further discussed below.

By spatial filtering the above system, the governing equations of LES are obtained. According to this approach, the large-scale turbulent structures in the flow field, which have a leading effect on the particle dispersion, are directly resolved on the grid. However, due to the extreme computational cost of the case under consideration we instead opted to perform Very-Large-Eddy Simulations (VLES). This effectively means that the applied filter and grid resolution are fine enough to resolve a substantial fraction of the energy-containing scales but not sufficiently fine to solve 80% of the total turbulent kinetic energy which would satisfy the definition of LES according to Pope [27]. Nevertheless, as it will be shown later, the applied resolution is sufficient for the purposes of our study.

In the last decades virtual boundary methods have been developed to handle complex geometries on a Cartesian grid [8,29]. Therein, the solid boundary, henceforth referred to as *wall*, is replaced by a body force ensuring the same boundary conditions, i.e. enforcing no-slip. In order to mimic the influence of the helicopter geometry on the airflow, we employ the immersed boundary method proposed by Revstedt [28] and Szasz et al. [37]. Therein surface meshes are generated for the solid boundaries. The body force which is included in the momentum equation is given by

$$\mathbf{F}_s = C_1(\mathbf{u}_s - \mathbf{u})e^{-C_2 d^2} \tag{2}$$