Aerospace Science and Technology 78 (2018) 580–592

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Analysis of the loads acting on the rotor of a helicopter model close to an obstacle in moderate windy conditions

D. Zagaglia [*], A. Zanotti, G. Gibertini

Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Campus Bovisa, Via La Masa 34, 20156 Milano, Italy

ARTICLE INFO

Article history:
Received 3 November 2017
Received in revised form 14 May 2018
Accepted 14 May 2018
Available online 16 May 2018

Keywords:
Helicopter
Interactional aerodynamics
Ground obstacles
Rotor loads
Ground effect
Wind tunnel

ABSTRACT

The present paper describes an experimental investigation of the loads acting on a rotor when it interacts with a simplified cuboid obstacle, representing a low-rise building, in moderate windy conditions. Measurements of forces and moments acting on the rotor were carried out by means of a six-component balance in order to assess the rotor performance for several helicopter positions with respect to the obstacle. Wind tunnel tests have been carried out at an advance ratio of $\mu = 0.05$ and compared with the corresponding wind-off tests. The investigation showed that ground effect on the obstacle is generally mitigated in windy conditions and that severe detrimental effects are encountered when the helicopter enters the obstacle wake, especially when the helicopter interacts with its lateral vortex structures.

1. Introduction

The helicopter is a very versatile flying machine which, thanks to its peculiar capability of managing hovering flight, is often required to operate within confined areas. Naval operations, e.g. the landing manoeuvre on a helicopter carrier, and rescue operations in confined areas, such as close to buildings and mountain walls, are typical operative conditions where the helicopter is forced to interact with the surroundings.

This aerodynamic interference between the rotor-induced wake and the surrounding obstacles typically generates a degradation of the helicopter performance and a high compensatory workload for the pilot [1]. In particular these helicopter/obstacle aerodynamic interactions can cause recirculating flows due to the deflection of the rotor-induced downwash, which can potentially lead to hazardous flight situations. These flight conditions can cause rapid trim changes leading to aircraft control difficulties, and potentially, collision with the obstacle itself. This situation can be further complicated by the presence of wind, since the helicopter has to interact with the complex, highly unsteady and turbulent wake generated by the obstacle.

Timm [2] was the first to observe the flow recirculation induced by the interaction between the rotor and obstacle through flow visualisations. More recently, the ground effect of a fully articulated rotor above a confined area between two vertical walls was investigated by Iboshi et al., [3].

The Dynamic Interface problem [4], i.e. the launch and recovery of flight vehicles, primarily rotorcraft, onto ships in windy conditions is probably the most investigated configuration from both the experimental and numerical point of view. Zan [5] produced one of the first experimental works on this topic, presenting the measurements of time-averaged rotor thrust coefficients for a rotor immersed in the airwake of the Canadian Patrol Frigate ship. This work shows how the interaction can significantly decrease rotor thrust up to 15%, thereby impacting operational envelopes. Zan proposed a set of changes in the ship superstructure geometry which were able to reduce the severity of the airwake and also lessen the spatial gradients of the rotor thrust coefficient. Further studies allowed to investigate also the unsteady loads on the fuselage immersed in the ship wake [6] and the full configuration comprising rotor and fuselage [7].

Other test rigs have been developed for the study of a helicopter in the airwake of a ship, like the one by Kääriä et al. [8,9]. In particular experiments were conducted in a water tunnel using a specially designed Airwake Dynamometer (AirDyn) to characterise the aerodynamic loading of the helicopter immersed in the shipwake, showing very strong variation of both average and unsteady loads due to the strong velocity gradients that develop in the wake of the ship.

The flow that is generated in the helicopter/obstacle interaction has been investigated as well. As an example, Quinliven and Long [10] investigated the inflow region and the wake of a ro-

---

[*] Corresponding author.
E-mail address: daniele.zagaglia@polimi.it (D. Zagaglia).

https://doi.org/10.1016/j.ast.2018.05.019
1270-9638/

Nomenclature

A	Rotor disk area, πR^2	m^2
c	Blade chord	m
c_∞	Asymptotic speed of sound	m/s
c_{Mx}, c_{My}	Rotor in-plane moment coefficients, $M/(\rho V_{TIP}^2 AR)$	
c_Q	Rotor torque coefficient, $Q/(\rho V_{TIP}^2 AR)$	
c_T	Rotor thrust coefficient, $T/(\rho V_{TIP}^2 A)$	
D	Rotor diameter	m
FM	Figure of Merit, $C_T^{3/2}/(C_Q\sqrt{2})$	
M_{TIP}	Mach number at blade tip, V_{TIP}/c_∞	
M_x, M_y	Rotor in-plane moments	N m
Q	Rotor torque	N m
R	Rotor radius	m
Re_{TIP}	Reynolds number at blade tip, $V_{TIP}c/\nu$	
T	Rotor thrust	N
U_∞	Free-stream velocity	m/s
V_{TIP}	Blade tip velocity, ΩR	m/s
(X, Y, Z)	Absolute reference system	
(x, y, z)	Rotor reference system	
ν	Fluid cinematic viscosity	m^2/s
ρ	Air density	kg/m^3
ϵ_{c_T}	Uncertainty on the Thrust coefficient	
ϵ_{FM}	Uncertainty on the Figure of Merit	
μ	Advance ratio, U_∞/V_{TIP}	
Ω	Rotational frequency of the rotor	RPM

tor in proximity of a building model, highlighting the effect of the flow-recirculation that occurs when the rotor is close to the building. Particle Image Velocimetry (PIV) was used by Rajagopalan et al. [11] to acquire 3-component velocity field measurements of the combined wake of a tandem-rotor helicopter and a ship. PIV was also used by Nacakli and Landman [12] to investigate the recirculation region between a rotor and the vertical wall of a ship deck. Measurements of the downwash and outwash from the rotor of a full-scale helicopter hovering near a land-based hangar were achieved by Polsky and Wilkinson [13].

Despite the presence of a fair number of numerical and experimental investigations, a systematic study of these aerodynamic phenomena is still lacking. Moreover the past studies usually involve very specific geometries (e.g. ship decks, specific buildings).

The idea behind the present work is thus to experimentally investigate this problem, simplifying the obstacle geometry up to a well-defined parallelepiped shape in order to disclose the key fluid-dynamic mechanisms that occur when a helicopter is hovering in its proximity. Similarly, a rigid unarticulated rotor was adopted, not allowing the flapping and lag blade motion which are quite difficult to be monitored on a small-scale model. In this way, the rotor geometry was *a priori* known and well-defined. Due to this choice, this very rigid hinge-less rotor with fixed pitch angle was untrimmed for helicopter equilibrium (also without the obstacle) and therefore it did not reproduce the dynamics of a real helicopter rotor. Nevertheless, the general features of its wake were still representative of those of a real one, thus the observed phenomena are not expected to be excessively affected by this choice. In the present work, the results will be referred to the corresponding (with or without wind) out of ground effect (OGE) condition, in order to identify the combined effect of both the ground and the obstacle and give an indication of the required pilot correction in a real case.

The aerodynamic behaviour of a complete, real helicopter is obviously very complex, due to the contribution of its different components such as the fuselage, the main rotor and the tail rotor, which interact with each other. A better understanding of each contribution can be obtained analysing separately their influence, thus generalising the observations and giving useful information for the development of flight control systems or simulation tools to be included in flight simulators. In light of these considerations, the present study was focused on the main rotor only. The tail rotor was not included in the model while a simple fuselage was present in order to create a more realistic rotor wake and shield the main model frame, which held the balance, the motor and its controller.

A first experiment [14] was initially carried out at Politecnico di Milano, analysing the case of a model helicopter with fuselage interacting with a cuboid obstacle in absence of wind. Subsequently, the present work intends to investigate how the phenomena that were observed in absence of external wind are affected by a moderate wind that flows past the obstacle.

To do so, a new test campaign was carried out in the framework of the GARTEUR AG22 action group [15], consisting in the analysis of a helicopter model interacting with a parallelepiped-shaped obstacle in both windy and not-windy conditions. Load measurements on the rotor were carried out in order to monitor the variations in the rotor performance for several helicopter model positions with respect to the obstacle. An additional database, analysing the interaction of a rotor without fuselage in absence of wind, was obtained at the University of Glasgow [16] in the framework of GARTEUR AG22 as well. The obtained databases are available on request so that they can be also used for the assessment of Computation Fluid Dynamics (CFD) codes as it has already been done, for instance, by Chirico et al. [17] with the previous test campaign of [14].

2. Experimental setup and test points

2.1. Experimental setup

The test rig that was used during the test campaign at Politecnico di Milano essentially consisted of a helicopter model and a parallelepiped obstacle which represented an ideal building, as represented in Fig. 1. The helicopter model was held by a horizontal strut fixed to a system of two motorised orthogonal sliding guides to allow the relative position to be changed with respect to the obstacle along the vertical and longitudinal directions of the fuselage. Two different reference systems are defined, as represented in Fig. 2. The global reference system (X, Y, Z) defines the position of the rotor hub centre with respect to the obstacle, whereas the rotor reference system (x, y, z) was used to define the force and moment components acting on the rotor. The origin of the absolute (X, Y, Z) coordinate system is fixed and it is placed on the floor, at the obstacle mid-span, so that the X-coordinate represents the distance of the rotor centre from the obstacle, the Y-coordinate represents the distance of the rotor centre from symmetry plane and the Z-coordinate represents the height of the rotor centre from the ground. Therefore the X–Z plane lies in the mid-span plane of the building model and the X–Y plane is coincident with the floor. The X coordinate grows as the helicopter is positioned further from the obstacle, the Y coordinate as the helicopter is positioned to the right of the obstacle and the Z coordinate as the helicopter is positioned upwards.

The tests were carried out in the large test chamber, suitable for wind engineering tests, of the Large wind tunnel of Politecnico di Milano (GVPM, see Reference [18]), as depicted in Fig. 3. The test chamber is 13.84 m wide, 3.84 m high and 38 m long. Despite the