MID-FIDELITY NUMERICAL APPROACH TO TILTROTOR AERODYNAMICS

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Abstract
The study of complex aerodynamics that characterise tiltrotors represents a challenge for computational fluid dynamics tools. URANS numerical solvers are typically used to explore the aerodynamic features that characterise the different flight conditions of these aircraft, but their computational cost limits their applications to a few vehicle configurations. The present work explores the capabilities of the new mid-fidelity aerodynamic code DUST, based on vortex particle method for wake modelling, to investigate the performance and flow physics of tiltrotors. A thorough assessment of the code capabilities was performed by comparison of numerical results with high-fidelity Computational Fluid Dynamics (CFD) data. This thorough comparison showed that the mid-fidelity numerical approach implemented in DUST is suitable for capturing flow physics related to the complex aerodynamic interactions between the proprotors and the wing along with the entire flight envelope of a tiltrotor.

1 INTRODUCTION

Tiltrotor aerodynamics is characterised by complex interactions between proprotors wake and wing that are peculiar of the different attitudes experienced by the vehicles during their flight mission. Indeed, tiltrotors combine the speed and range of a conventional fixed-wing aircraft with the vertical take-off and landing capabilities of helicopters. Consequently, the study of interactional aerodynamics that characterise tiltrotors represents a challenge for computational fluid dynamics tools. High-fidelity numerical solvers were typically used to explore the complex interactions between rotors wake and wing that are peculiar of the different attitudes reproduced by these aircraft during their flight mission [1, 2, 3, 4, 5]. Nevertheless, the computational cost of high-fidelity CFD simulations for such configurations precludes their applications to a limited number of vehicle configurations. Recently, the interest about mid-fidelity aerodynamic solvers has grown in the field of rotorcraft simulations. As a matter of fact, due to the limited computational effort required by these numerical tools, they are suitable to be used to perform the large number of aerodynamic simulations required for preliminary design of novel rotary-wing vehicles. In particular, a new flexible mid-fidelity computational tool called DUST was developed as the result of a collaboration between Politecnico di Milano and A^3 by Airbus LLC aimed to develop a fast and reliable numerical tool for aerodynamic simulations of complex rotorcraft configurations as eVTOLs aircraft [6, 7]. DUST is an open source code simultaneously involving different aerodynamic modelling techniques as thick surface panels, thin vortex lattices and lifting lines for solid bodies, while vortex particles [8] are used for wake modelling. The complete mathematical formulation of DUST code is described in [9]. The present work is aimed to assess the accuracy of the mid-fidelity approach implemented in DUST with respect to high-fidelity CFD tools in order to show the suitability of this code for preliminary design of novel tiltrotor configurations. Such validation of the present numerical tool was performed in the framework of the EU funded CleanSky 2 FORMOSA project [10] aimed to the design of a novel wing movable surface system for the NextGen Civil Tiltrotor aircraft developed in the frame of Clean Sky 2 – H2020 Programme. In particular, due to the accessible and comprehensive data available in literature, the test case considered in the present work is the XV-15 aircraft. DUST simulations over the complete flight envelope of this tiltrotor aircraft are compared with high-fidelity numerical results reported in the works by Tran et al. [11, 12]. The numerical activity performed with DUST considered steady state conditions of the complete XV-15 tiltrotor aircraft in hover, conversion and cruise conditions.

2 NUMERICAL MODEL

The numerical model of the XV-15 tiltrotor was built considering the full scale dimensions and all the aircraft components. The model included the fuselage with a length of 14.1 m, the horizontal and vertical tailplanes, the wing equipped with control surfaces (i.e. flap and flaperon) and the two proprotors with nacelles, as shown in the mesh layout presented in Fig. 1.

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	Wing	Horizontal Tail	Vertical Tail
Airfoil	NACA 64A223	NACA 64015	NACA 0009
Span	9.8 m	3.91 m	2.34 m
Mean aerodynamic chord	1.60 m	1.20 m	1.13 m
Sweep ($c/4$)	$-6.5°$	$0°$	$31.6°$
Dihedral	$2.0°$	$0°$	-
Incidence	$3.0°$	$0°$	$0°$
	Flap	Flaperon	
Span along hinge line	1.30 m	2.40 m	
Chord/Wing chord	0.25	0.25	
Maximum deflection	$75°$	$47°$	

Table 1: Geometrical features of the XV-15 tiltrotor numerical model.

Flight condition	V_∞	Vehicle pitch attitude (α_V)	Nacelle angle (θ_N)	Rotor speed Ω	Flap angle	Flaperon angle
Hover	0 knots	$0°$	$90°$	589 RPM	$40°$	$25°$
Conversion	40 knots	$8.569°$	$75°$	589 RPM	$40°$	$25°$
Cruise	160 knots	$4.332°$	$0°$	517 RPM	$0°$	$0°$

Table 2: Parameters of the full XV-15 vehicle configurations considered for DUST numerical simulations.

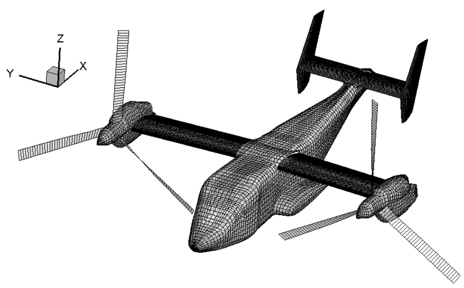


Figure 1: Layout of the mesh for DUST simulations of the full XV-15 tiltrotor.

The main characteristics of the full vehicle geometry, including the airfoil series used to build the numerical model, are reported in Tab. 1. DUST simulations performed in the present work do not include the Gurney flap on the wing present during flight tests [13], as reported by Tran and Lim [11]. The proprotors blades for the full vehicle simulations were modelled using 35 lifting line elements. All the remaining components of the vehicle were modelled using surface panels. Details about aircraft mesh and convergence studies are reported in [14]. Simulations were advanced in time using a discretisation of 40 time steps for rotor revolution for a total simulation length of ten rotor revolutions. The computational time for a single flight condition of the full vehicle was about 80 minutes over a workstation equipped with a Intel® Core™ i9-9980XE processor running on a base frequency of 3.00 GHz, with 18 physical cores and 2 threads for each core. DUST simulations considers the three different flight conditions that characterise tiltrotor mission, i.e. hover, conversion and cruise. In particular, simulations reproduced the hover and cruise flight parameters used in the high-fidelity CFD simulations performed by Tran et al. [12] and the conversion mode parameters of the CFD simulations performed by Tran and Lim [11]. A summary of the flight parameters reproduced in DUST simulations are shown in Tab. 2, where their definitions are illustrated in the aircraft sketch shown in Fig. 2. For a thorough comparison of the results, the blade azimuthal angle definition and the reference system used in this work is the same of the ones used in the reference works [12, 11].

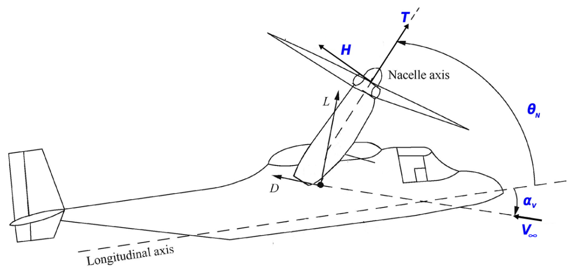


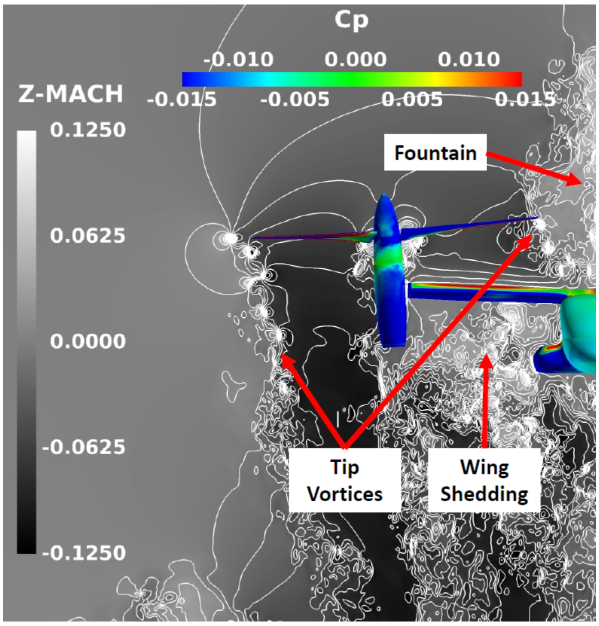
Figure 2: Definition of the main parameters of the full XV-15 tiltrotor configuration.

The test conditions were considered from the Generic Tiltrotor (GTR) flight simulations data provided by Ferguson [15]. Following the same procedure suggested by the CFD works [12, 11], for DUST simulations the thrust (T) and H-force (H) on the proprotors are trimmed to simulator data [15] by adjusting the rotor collective and longitudinal cyclic pitch angles. The lateral cyclic pitch angle was set to zero for all the simulated configurations, since the lateral cyclic control was not installed on the XV-15.

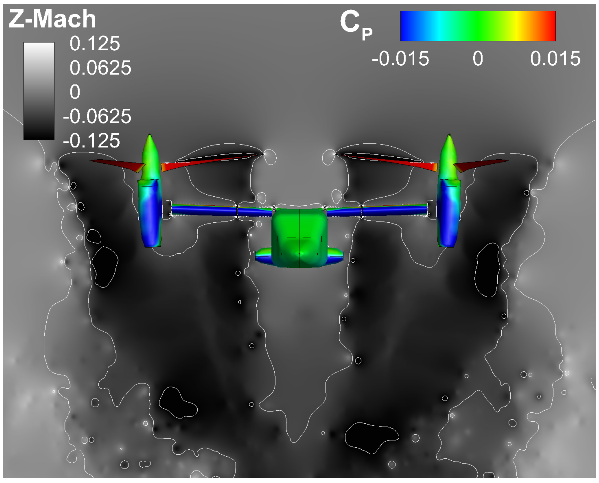
3 RESULTS AND DISCUSSION

3.1 Hover

Figure 3 shows the comparison of the contours of the instantaneous vertical velocity component around the vehicle computed in hover for blade azimuth $\psi = 270°$ over a Y_Z plane passing through the nacelle axis.



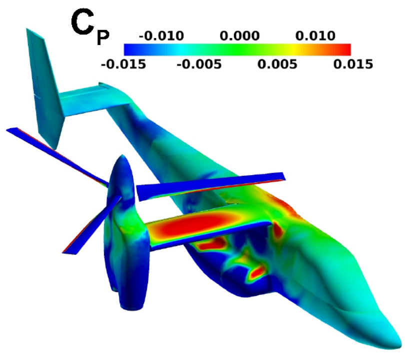
(a) Half-span model- CFD [12]



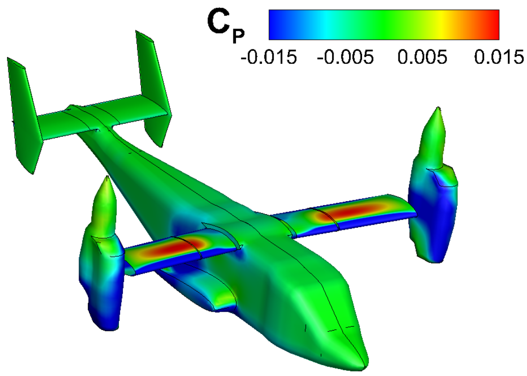
(b) Complete model - DUST [14]

Figure 3: Comparison of the contours of the vertical velocity component around the vehicle in hover at $\psi = 270°$, $\theta_N = 90°$, Ω = 589 RPM.

DUST representation resembles quite well the global behaviour of the flow field around the vehicle computed by high-fidelity CFD. In particular, DUST results show a flow region over the fuselage characterised by a quite moderate upwash that is a typical flow feature of tiltrotor configurations well known as fountain flow [3]. The size and strength of the fountain flow is greater in half-span CFD models due to the reflection of the flow caused by the symmetry boundary condition [3]. Indeed, a significant higher upwards velocity region over the fuselage is observed from high-fidelity CFD results, as can be observed from Fig. 3(a). Generally, DUST showed a good capability to reproduce the quite complex flow field around the complete vehicle that characterise this flight condition with a quite limited computational time with respect to high-fidelity CFD simulations.



(a) Half-span model- CFD [12]



(b) Complete model - DUST [14]

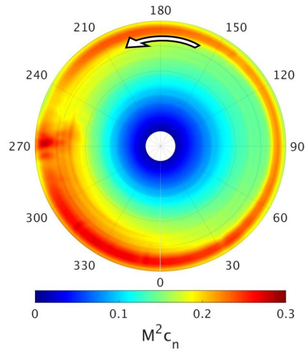
Figure 4: Comparison of the contours of the pressure coefficient C_p on the vehicle surface in hover at $\psi = 270°$, $\theta_N = 90°$, Ω = 589 RPM.

The aerodynamic interference of the wing on the rotor downwash provides a significant download on the vehicle that has to be overcome in hover and climb flight conditions. Figure 4 shows the comparison of the instantaneous surface pressure coefficient C_p on the fuselage computed in hover condition by DUST and high-fidelity CFD at blade azimuth $\psi = 270°$. A large high pressure region covering almost all the wing surface can be observed due to the impingement of the rotor wake. The high-pressure region extent and the positive C_p values over the wing are quite higher for high-fidelity CFD with respect to DUST. Consequently, the download on the wing computed by DUST is underestimated with respect to high-fidelity CFD. Indeed, DUST computed a download on wing equal to 3% of the global proprotor thrust instead of 10.3% computed by high-fidelity CFD. This difference should be related to an incorrect prediction of the aerodynamic effects related to wing surface that is normally invested by proprotor wake. Nevertheless, the quite complex flow conditions around the wing characterised by strong shedding regions with low flow velocities and low Reynolds numbers have to be considered difficult to be represented with potential methods. Moreover, high-fidelity CFD shows a higher pressure region over the upper surface of the fuselage (see Fig. 4(a)) due to an higher strength of fountain flow effect related to the use of an half-span CFD model.

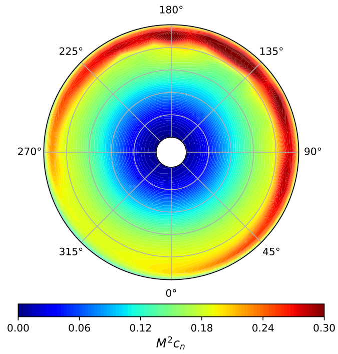
The proprotor aerodynamic performances in hover are analysed in Fig. 5, showing the comparison of the contours of the blade non-dimensional normal force (M^2c_n) and pitching moment (M^2c_m) computed over the last rotor revolution. The general behaviour of the polar distributions of normal force and pitching moment computed by high-fidelity CFD is captured by DUST simulation. Nevertheless, CFD results show a sudden fluctuation for both normal force and pitching moment, particularly apparent in the azimuthal region around $\psi = 270°$. As indicated by Tran et al. [12], these fluctuations are related to the combination of blade passage through the high pressure region over the wing and to the fountain flow reingestion. The amplitude and dynamics of the impulsive loading of the blades could be overestimated by CFD due to the greater size and strength of the fountain flow related to the half-span model, as indicated in [3]. On the other hand, since the fountain size and dynamics are weaker for the full-span vehicle, DUST simulations results do not show these fluctuations in this azimuthal region and the global behaviour of the normal force and pitching moment are smoother with respect to high-fidelity CFD results.

3.2 Conversion mode

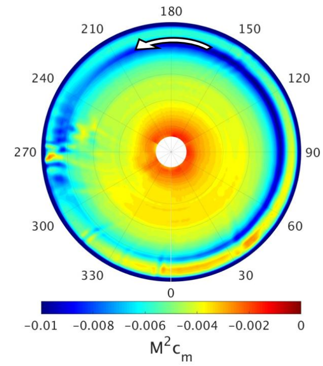
The analysed conversion mode flight condition is characterised by the combination of high incidence angle of the nacelle $\theta_N = 75°$ with low freestream velocity V_∞ = 40 kts, providing complex vortex interactions. Indeed, the vortices issued by the proprotor blades quickly wrap up into a pair of "disk vortices" starting particularly nearly to $\psi = 90°$ and $\psi = 270°$. This feature, highlighted by high-fidelity CFD results [11], is clearly captured by DUST simulation results, as shown by the instantaneous flow field computed at $\psi = 270°$ represented by the iso-surface of Q-Criterion in Fig. 6. In particular, at $\psi = 90°$ and $\psi = 270°$ a proprotor blade interacts significantly with the vortices issued by the second and third blade of the proprotor passing simultaneously on both the upper and lower surface of the rotor blade (see Fig. 6(b)). The flow physics of this interaction is quantitatively captured by DUST simulation if compared to high-fidelity CFD results shown in [11]. The formation of disk vortices create interactional effects on proprotors blades in terms of large variations of normal force. This effect is clearly visible from the comparison of the blade M^2c_n computed at $r/R = 0.95$ shown in Fig.7.



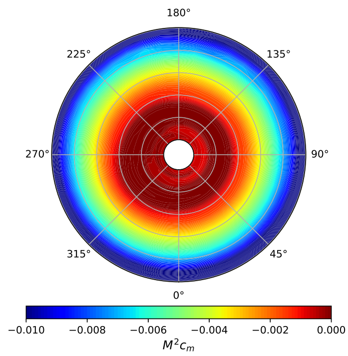
(a) M^2c_n - CFD [12]



(b) M^2c_n - DUST [14]

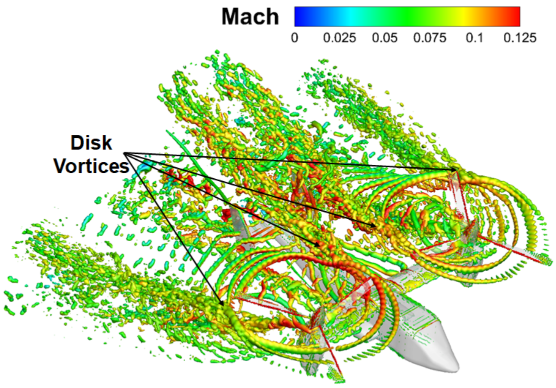


(c) M^2c_m - CFD [12]

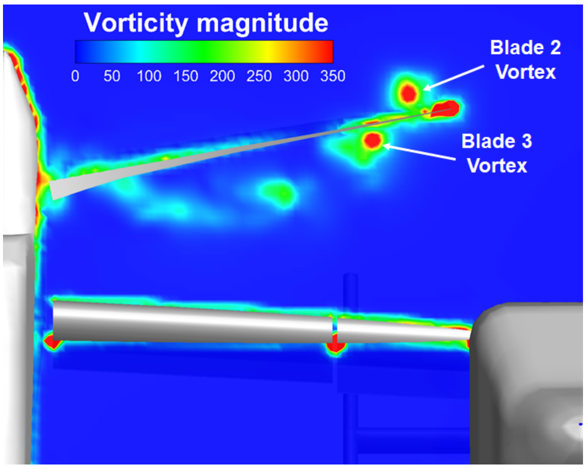


(d) M^2c_m - DUST [14]

Figure 5: Comparison of the contours of the non-dimensional normal force M^2c_n and pitching moment M^2c_m on the proprotor blade in hover, $\theta_N = 90°$, Ω = 589 RPM.



(a)



(b)

Figure 6: Instantaneous flow field computed by DUST in conversion flight condition at $\psi = 270°$, $\theta_N = 75°$, V_∞ = 40 kts, Ω = 589 RPM (from [14]); (a) iso-surface of Q-Criterion, (b) iso-contours of vorticity on a slice cutting the nacelle axes.

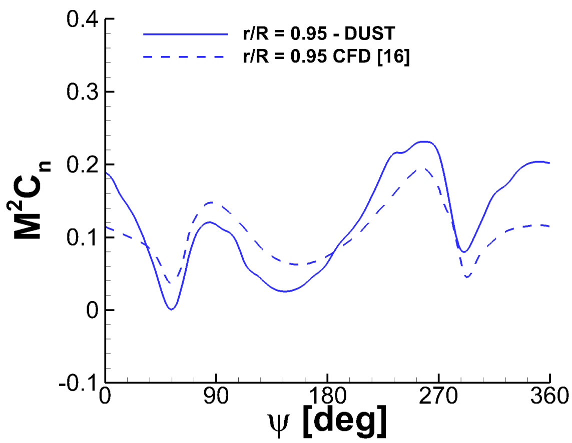
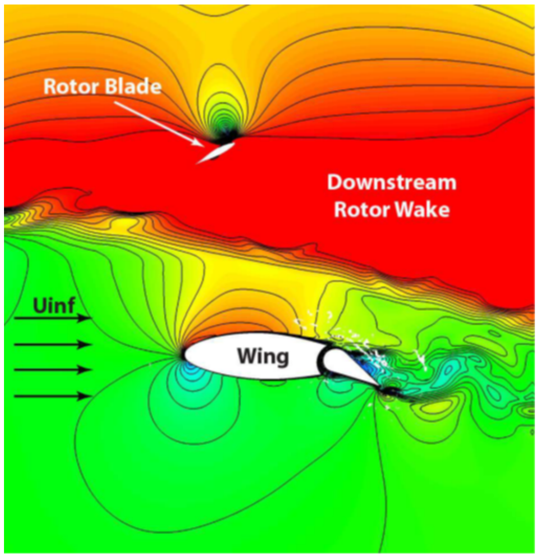
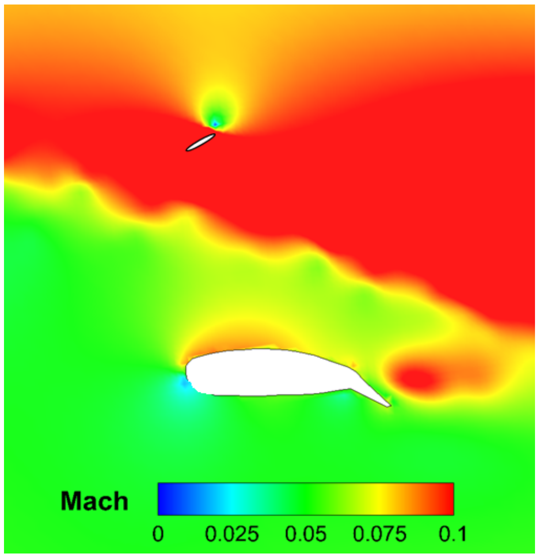


Figure 7: Comparison of the time histories of the non-dimensional normal force M^2c_n on the proprotor blade in conversion flight condition at $r/R = 0.95$, $\theta_N = 75°$, V_∞ = 40 kts, Ω = 589 RPM (from [14]).

DUST simulations capture well the occurrence and the amplitude of the normal force variations around $\psi = 90°$ and $\psi = 270°$ computed by high-fidelity CFD (see Fig. 7). In order to evaluate the aerodynamic effect on flow field due to interaction between proprotor wake and wing, Fig. 8 shows the comparison of the instantaneous flow field on a slice cutting longitudinally the wing at midspan.



(a) CFD - [11]



(b) DUST [14]

Figure 8: Comparison of the instantaneous flow field at wing midspan in conversion flight condition at $\psi = 270°$, $\theta_N = 75°$, V_∞ = 40 kts, Ω = 589 RPM.

A quite good agreement is observed between high-fidelity CFD and DUST flow field representations showing, for this flight condition, that the proprotor wake is advected downstream completely missing the wing. Nevertheless, DUST results do not show the limited separated flow region over the upper surface of the deflected flap.

3.3 Cruise

In cruise condition, the proprotor wake is advected downstream and shows a coherent helical structure of the vortices issued by the blade tips that invest the wing. This flow behaviour is clearly reproduced by DUST simulations, as shown by iso-surface of the Q-criterion illustrated in Fig. 9 for $\psi = 270°$. Moreover, as wing control surfaces are not deflected and nacelle axis is aligned with freestream velocity, the shedding from the nacelle is clearly visible.

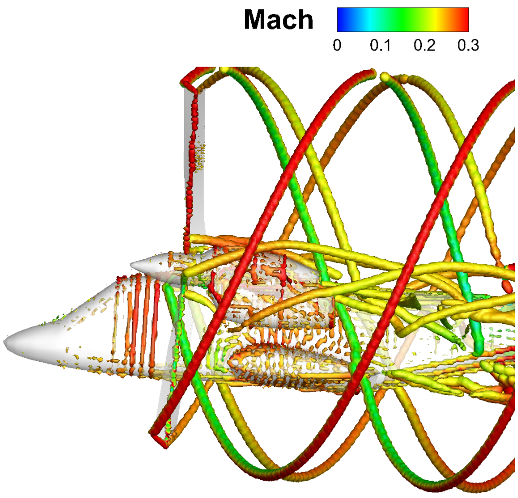
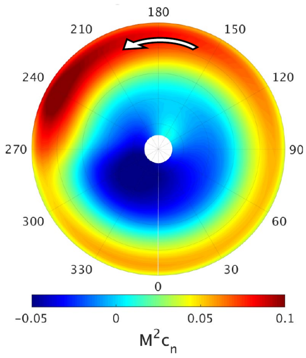
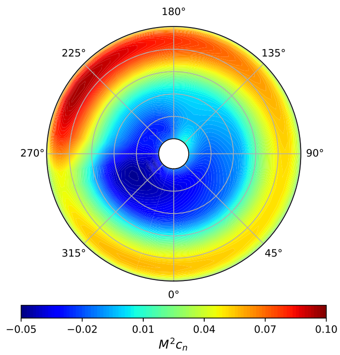


Figure 9: Instantaneous flow field computed by DUST in cruise flight condition at $\psi = 270°$, $\theta_N = 0°$, V_∞ = 160 kts, Ω = 517 RPM; iso-surface of Q-Criterion (from [14]).

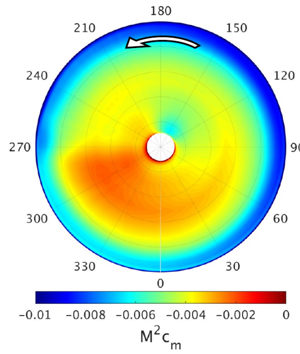
The aerodynamic interaction between proprotors and wing provides an effect also on blade performances. Indeed, in cruise mode the presence of a thick airfoil, as for the XV-15 tiltrotor configuration, produces a blockage effect that generates an effective upwash when the blade passes over the wing. This results in a positive peak in the normal force produced by the proprotor that occurs once per revolution on each blade. Moreover, due to the wing aerodynamic circulation, a doublet wash on the normal velocity of the blades, i.e. an upwash followed by a downwash, occurs when the blade passes in front of the wing, thus producing a local unsteady doublet of the blade normal force [16]. As can be observed from the comparison of the contours of blade non-dimensional normal force and pitching moment computed over the last rotor revolution shown in Fig. 10, a doublet loading related to the passage of the blade in front of the wing is particularly apparent for M^2c_n. This feature and the general behaviour of the loads polar distributions computed by DUST and high-fidelity CFD are in quite good agreement, with some limited discrepancies observed for the pitching moment only. The outcomes of this comparison confirm the capabilities of the mid-fidelity approach implemented in DUST to reproduce the flow features related to proprotor/wing interactions and to capture the behaviour of the rotor aerodynamic performances also for aircraft cruise condition.



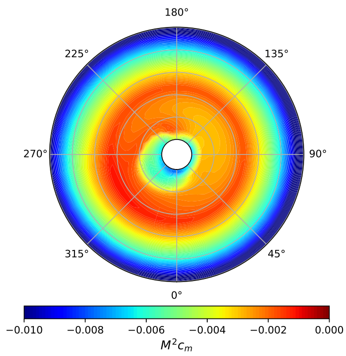
(a) M^2c_n - CFD [12]



(b) M^2c_n - DUST [14]



(c) M^2c_m - CFD [12]



(d) M^2c_m - DUST [14]

Figure 10: Comparison of the contours of the non-dimensional normal force M^2c_n and pitching moment M^2c_m on the proprotor blade in cruise, $\theta_N = 0°$, V_∞ = 160 kts, Ω = 517 RPM.

4 CONCLUSIONS

A thorough assessment of the capabilities of a mid-fidelity numerical approach to evaluate aerodynamic performances and flow physics of a tiltrotor was performed in the present work by comparing results of numerical simulations performed using the mid-fidelity aerodynamic solver DUST with high-fidelity CFD data available in recent literature. The simulation results comparison was performed over different steady flight configurations that characterise the flight mission of the XV-15 tiltrotor aircraft. For hover flight condition, DUST simulation results demonstrate the capabilities to reproduce the overall complex aerodynamic flow around the vehicle. Nevertheless, a high underestimation of the wing download was observed from DUST simulations with respect to high-fidelity CFD that could be related to an incorrect prediction of the complex flow conditions around the wing characterised by low velocities and massive shedding regions. The results of numerical simulations performed over the first stage of the aircraft conversion corridor and in cruise condition showed great accuracy of DUST simulations results concerning the representation of the interactional flow features characterising this flight condition and their effects on proprotor aerodynamic loads. Consequently, the outcomes of the present work clearly indicate that mid-fidelity solvers based on VPM are suitable to be used in the preliminary design of novel VTOL aircraft architectures as tiltrotors, requiring a large number of configurations to be investigated and characterised by complex aerodynamic interactions.

ACKNOWLEDGMENTS

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