

**WING-ROTOR AERODYNAMIC INTERFERENCE ON A
TILTWING AIRCRAFT IN THE FIRST PART OF CONVERSION
MANOEUVRE**

G. Droandi*, G. Gibertini*, D. Grassi*, G. Campanardi*, C. Liprino*, M. Bertagnini*

*Dipartimento di Scienze e Tecnologie Aerospaziali – Politecnico di Milano
Campus Bovisa, Via La Masa 34, 20156 Milano, Italy
e-mail: giovanni.droandi@polimi.it

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Abstract

Tiltwing aircraft represents a possible future evolution of conventional tiltrotors. Indeed, by making use of smaller rotors, a tiltwing is able to hover in helicopter mode, to achieve very high forward speed in cruise flight in aeroplane mode and to allow for horizontal taking off and landing. The partial tilting wing concept, introduced in 2000 in the ERICA tiltrotor design, made the tiltwing solution even more attractive. Although this promising configuration was widely studied, many aspects require further analysis. In the present work, the initial stage of the transition manoeuvre that allows a tiltwing aircraft employing the partial tilting wing solution to convert from helicopter to aeroplane mode is investigated. An extensive wind tunnel test campaign carried out in the Politecnico di Milano Large Wind Tunnel is described and the effects due to the aerodynamic interaction between wing and rotor are discussed. Aircraft performance are also discussed to assess the effectiveness of this aircraft design.

NOMENCLATURE

A	=	Rotor disk area
C_{Fz}^R	=	Rotor Z-force coefficient, $F_Z^R/(\rho A \Omega^2 R^2)$
C_{Fx}^W	=	Half-wing X-force coefficient, $F_X^W/(\frac{1}{2}\rho S U_\infty)$
C_{Fz}^W	=	Half-wing Z-force coefficient, $F_Z^W/(\frac{1}{2}\rho S U_\infty)$
F_{Weight}^A	=	Half-aircraft weight
F_Z^{FT}	=	Half-Fuselage and tail X-force
F_X^N	=	Nacelle X-force
F_Z^N	=	Nacelle Z-force
F_X^R	=	Rotor X-force
F_Z^R	=	Rotor Z-force
F_X^W	=	Half-wing X-force
F_Z^W	=	Half-wing Z-force
μ	=	Advance ratio, $U_\infty/(\Omega R)$
N_b	=	Number of blades
Ω	=	Angular speed
R	=	Rotor radius
ρ	=	Air density
τ^N	=	Nacelle angle of attack
τ^W	=	Tilting wing angle of attack
S	=	Half-wing surface
U_∞	=	Free stream velocity

1 INTRODUCTION

A tiltrotor is an hybrid configuration aircraft that can alternatively fly like a helicopter and an aeroplane being able to take-off and land vertically and to flight in cruise at high speed. Such a machine has the potential to revolutionise the air transportation since it would combine the flight performance of modern propeller driven aeroplanes with the versatility and control characteristics of common helicopters [1]. Aeronautical industries, research institutions and universities had investigated the tiltrotor concept for more than forty years, working out most of the basic engineering problems. Successful designs, such as the XV-15, V-22 Osprey and AW609, gave a new pulse to the research on this type of hybrid aircraft but several different areas require further development and analysis.

One of the most important features characterising tiltrotors is represented by the aerodynamic interaction between the wing and large rotors. This phenomenon has been broadly investigated using both experiments [2, 3] and calculations [4], although analyses were mainly focused on helicopter operative mode and hovering condition. Moreover, many research activities have been developed in

order to reduce the download force acting on the wing caused by the interaction with the rotor wake [5, 6].

During the past years, unconventional tiltrotor configurations have been widely investigated. In these regards, the most interesting alternative solution to conventional tiltrotors has been the tiltwing aircraft characterised by small propellers installed on a tilting wing, such as the VZ-2, XC-142 and CL-84. Thanks to its peculiar configuration, a tiltwing aircraft was able to hover in helicopter mode and to achieve very high forward speed in cruise flight in aeroplane mode allowing also for horizontal taking off and landing.

Nowadays, the attractive idea of tiltwing aircraft represents a possible future evolution of tiltrotors. In this framework, the research project ERICA (Enhanced Rotorcraft Innovative Concept Achievement [7]) founded by the European community was started at the beginning of the 2000s. The main objective of this project was the design of an innovative aircraft employing the tiltwing concept [8] and using a modular wing that can be partially rotated. Even though this aircraft configuration was widely studied [9, 10, 11], many aspects require further analysis. Furthermore, the huge amount of data collected during the ERICA project has not been made public as their distribution was restricted to the member of the consortium. A fundamental investigation of the effects due to the aerodynamic interaction between wing and rotor of a tiltrotor aircraft employing the partial tiltwing solution would represent an useful contribution for the rotorcraft community.

In 2011 a research activity was started at Politecnico di Milano to carry out an in depth study on the mutual aerodynamic interference between rotor and wing of a tiltwing aircraft [12]. For this purpose, a tiltwing aircraft being representative of a new generation V/STOL aircraft in the same class of the ERICA was considered. The first part of the research activity was aimed at studying the hovering flight condition using both wind tunnel experiments [13] and computational fluid dynamics (CFD) calculation [14]. The effectiveness of the partial tilting wing solution was demonstrated in helicopter mode as it allowed to minimise the wing download. The wing/rotor aerodynamic interaction was then further investigated taking into account the first stage of the conversion manoeuvre that allows the aircraft to convert from the helicopter to the aeroplane configuration.

The present paper describes the tiltwing aircraft performance during the first phases of the transi-

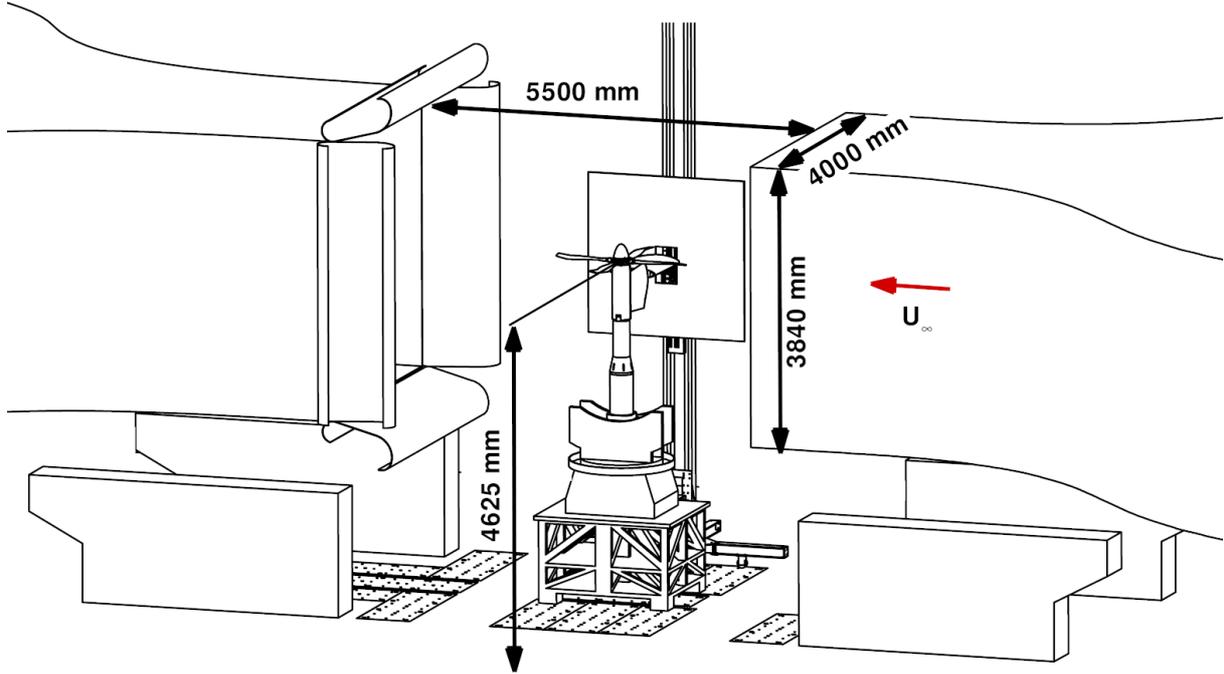


Figure 1: Wind tunnel test layout.

tion manoeuvre and discussed the effects produced on both wing and rotor by their mutual aerodynamic interaction. Rotor and wing airloads as well as rotor kinematic parameters were measured during an extensive wind tunnel measurement campaign performed in Politecnico di Milano Large Wind Tunnel (GVPM). In this regard, a parametric study was carried out taking into account different advance ratios μ , nacelle angles of attack τ^N and tilting wing angles of attack τ^W .

2 AIRCRAFT LAYOUT

As already mentioned, the main objective of the present research activity was a overall evaluation of the partial tilting wing concept applied to a tiltrotor aircraft. For this purpose, a new tiltwing aircraft [12] was designed to be a civil passenger transportation aircraft having a gross weight of 11600 kg and able to carry a maximum of 22 passengers with luggage (corresponding to a payload of 2200 kg). The point to point service taken from and to vertports represented a typical mission profile for this aircraft. Such a tiltwing was characterised by a pair of small diameter (7.4 m at full-scale), wingtip mounted proprotors and a partially tilting wing with a span of 15 m.

Advanced aerodynamic optimisation procedures

were employed to design both proprotor blades and tilting wing shape. In particular, rotor blades were designed making use of a multi-objective optimisation procedure found on a genetic algorithm, as described by Droandi and Gibertini [15]. A parametric study was then carried out to identify the best wing configuration [12]. Indeed, the span-wise location of the tilting wing section was chosen performing CFD calculations on different wing configurations. The tilting wing section of the resulting wing was located 3.732 m from the aircraft symmetry plane. The wing was linearly tapered, untwisted and unswept and all the wing sections were aligned with respect to the 25 % of the local chord.

3 TEST RIG SETUP

A wind tunnel half-span model [13] reproducing the tiltwing aircraft described in the previous section was designed and manufactured at the Department of Aerospace Science and Technology (DAER) Aerodynamic Laboratory. Experimental tests were carried out in the open test section of the GVPM which is an atmospheric closed loop wind tunnel (maximum wind velocity achievable is 55 m/s), with a test section of 4 m \times 3.84 m. A schematic view of the wind tunnel test layout is depicted in Figure 1. A picture of tiltwing half-

span model installed in the open test section of the GVPM is shown in Figure 2 taken with the outer wing and the rotor tilted at different angles. The 1/4-scaled half-span model represented one rotor, the nacelle and the corresponding half-wing. The test rig essentially consist of two main components completely separated: a whirl tower (driving the four-blade rotor) and the half-wing model. The rotor model ($R = 0.925$ m) was located on a support which was composed by an aluminium base, a swivelling base and a rigid pylon. The swivelling base allowed to rotate the pylon and the rotor hub about the rotor hub centre. Such degree of freedom (maximum angular displacement 22.5°) enabled to change the nacelle angle of attack τ^N keeping unchanged the distance between the rotor hub centre and the ground ($5 R$). The rotor model was fully articulated and Hall effect sensors were used to measure the actual blade pitch, flap and lead-lag angles during the tests. Rotor airloads were measured using a six-component holed balance mounted below the rotor hub. The torque was measured by an instrumented shaft passing through the balance and joined to the transmission shaft by a torsionally stiff steel laminae coupling that avoided the transmission of axial force through the rotor shaft.

The half-wing system was composed by the aircraft half-span wing and an image plane. According to the model geometrical scale, the half-span wing model had a root chord of 0.750 m and a tip chord of 0.520 m. The fixed wing had a span of 0.933 m while the tilting part has a span of 0.792 m. The axis passing through 25 % of the local chord corresponded to the wing rotation axis, as sketched in Figure 3, so that the outer wing portion could be easily rotated about the rotation axis by 15° steps. Finally, a squared wooden plane was placed in correspondence of the half-wing root section and was fixed to the wing support in attempting to reproduce the full-span aircraft behaviour.

In Figure 3 the aircraft reference system is also shown. The X-axis was aligned with the chord of the fixed wing root and directed toward the wing trailing edge. As the angle of attack of the fixed wing was kept equal 0° during all the test campaign, the X-axis also corresponded to the wind direction. Rotor and wing static forces and moments were computed with respect to the aircraft reference system. No corrections were applied to rotor and wing static forces and moments for rotor pylon, wing strut and wind-tunnel effects.

Although a general idea of the whole aircraft was outlined, a proper definition of its flight dynam-



Figure 2: The tiltwing half-span model in the open test section of the Politecnico di Milano Large Wind Tunnel.

ics was outside the aim of the present study. A conversion corridor for the tiltwing aircraft considered in the present work was not established and a well defined set of conditions to be tested was not available. Therefore, a set of conditions "reasonably close" to a possible transition manoeuvre that would allow the aircraft to convert from hovering to aeroplane flight mode were identified and included in the experimental test matrix. In particular, the test matrix of the measurement campaign was defined taking into account the conversion manoeuvre of the XV-15 [16] and ERICA [10] tiltrotors. In Figure 4 the trim conditions tested at GVPM are illustrated and compared with those tested at DNW in the frame of the NICETRIP project [10]. The experimental tests consisted in rotor thrust sweeps (the thrust variation is obtained by controlling the collective pitch angle) carried out at a certain setting of nacelle incidence τ^N , tilting wing incidence τ^W and advancing ratio μ keeping the fixed part of the wing at zero angle of attack. During the tests, the rotor was controlled by the swashplate and for each prescribed collective pitch angle it was trimmed to avoid the flapping motion

4 RESULTS

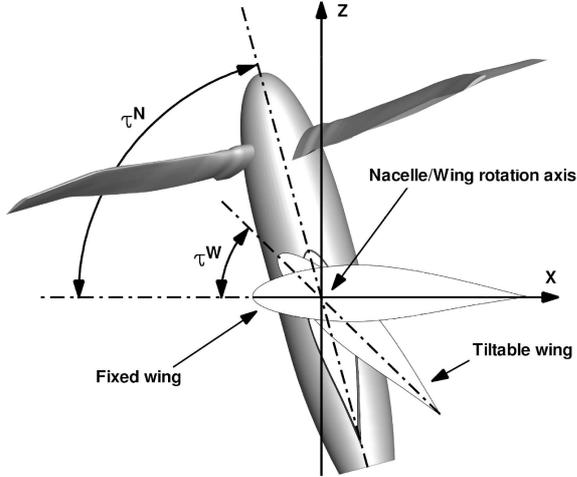


Figure 3: Sketch of the fixed/tilting wing and rotor and aircraft reference system.

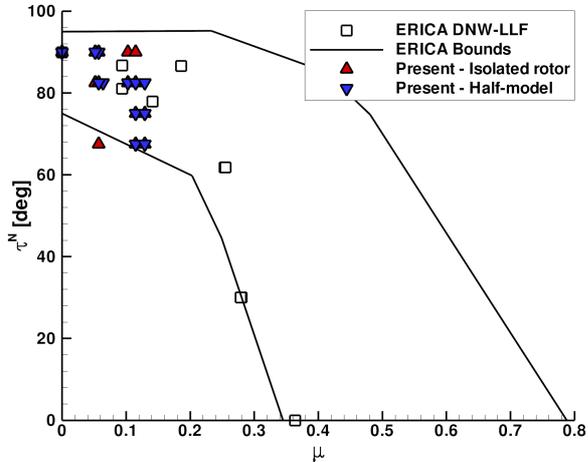


Figure 4: Isolated rotor and half-span model test conditions at GVPM and ERICA flight envelope and test conditions at DNW [10].

(i.e. zero 1/rev flapping). Since rotor rotational speed ranged between 800 rpm and 1000 rpm and wind tunnel free stream velocity was limited between 5 m/s and 10 m/s, corresponding advancing ratios μ ranged between 0.052 and 0.129.

Wind tunnel data gathered at GVPM during the experimental tests are reported and discussed in this section. The test conditions were defined as a combination of three different parameters: the advance ratio μ , the nacelle angles of attack τ^N and the tilting wing angle τ^W . For each test condition a thrust sweep (ranging from zero to a maximum thrust value achievable by the rig) was performed. Each measurement point of each thrust sweep was obtained by trimming the rotor to avoid the blade flapping motion. The fixed wing angle of attack was kept equal to zero in all the tests.

Previous studies carried out in the hovering condition [13, 14] demonstrated the effectiveness of the tilting wing solution with respect to the conventional tiltrotor layout. One of the most important advantages in hovering was represented by the strong reduction of the wing download. It was found that the download produced by the rotor wake impinging on the wing was minimised (less than 1 % of the rotor thrust) when the outer part of the wing was placed at 90° of incidence. On the other hand, present results revealed a more complex behaviour of the rotor/wing system when the aircraft was in the first phases of the conversion manoeuvre. Indeed, it was observed that the interaction between wing and rotor during the transition manoeuvre depended on both the flight condition and the aircraft configuration. More in details, the rotation of the outer wing portion allowed the wing to develop high lift values in forward flight. However, the rotation of the wing produced non-negligible drag forces that increased as the wing angle of attack τ^W increased. Indeed, the strong oblique wind resulting from the free stream and the rotor wake system produced on the wing a local lift (normal to the local wind) that led to a non-negligible wing drag force component.

The wing behaviour is presented analysing both the Z and the X force coefficients (corresponding to lift and drag coefficients) of the wing only. Such coefficients are plotted in Figure 5 as function of the rotor vertical force coefficient. In order to compare wing and rotor coefficients, the latter were re-normalised to be coherent with the wing coefficient (as explicitly written in the axis label).

Figure 5(a) and 5(b) compare two different conditions having the same advance ratio $\mu = 0.115$ and nacelle angle $\tau^N = 82.5^\circ$ but different tilting wing angle (60° and 75°). As it is apparent, both wing configurations exhibited good lifting capabilities. However only the configuration having

$\tau^W = 60^\circ$ allowed the aircraft to correctly accelerate (see Figure 5(b)). A similar conclusion can be drawn for the case having $\mu = 0.115$ and nacelle angle $\tau^N = 75^\circ$. Figure 5(c) and 5(d) compare the wing vertical and horizontal force components obtained with the outer wing placed alternatively at 0° , 60° and 75° . The comparison between the untilted wing configuration and the two tilted configurations confirmed the effectiveness of the partial tilting wing solution that allowed to develop high lift forces by rotating the outer part of the wing. Figure 5(e) and 5(f) present the comparison between four different wing configuration at a lower nacelle angle ($\tau^N = 67.5^\circ$) and higher advance ratio ($\mu = 0.129$). Also in this case the untilted wing configuration produced very small lift values with respect to the other wing configurations.

The advantages produced by a proper setting of the tilting wing angle τ^W are apparent from the pictures depicted in Figure 5. Indeed, as can be clearly observed in Figure 5(a), 5(c) and 5(e), when the wing assumed high angles of attack (for instance 60° and 75°) its vertical force coefficient reached maximum values of the order of 20 % of the re-normalised rotor vertical force coefficient. Small values were reached when the outer wing was placed at lower angles of attack (see Figure 5(e)). On the other hand, significant differences were observed between all the wing configuration tested in terms of wing horizontal force coefficient (Figure 5(b), 5(d) and 5(f)). In particular, when $\tau^W = 75^\circ$ the wing produced a maximum horizontal (drag) force which was twice the horizontal (drag) force given by the wing having $\tau^W = 60^\circ$.

During the tests, only the forces produced on both the wing and the rotor were measured. In order to make some general considerations on the aerodynamic behaviour of the aircraft, the contributions of other parts of the whole aircraft were estimated. In particular, the drag coefficient of the fuselage (with the tail) was assumed to be constant and equal 0.035 while the fuselage lift coefficient was considered negligible. The aerodynamic force produced by the nacelle was calculated by considering it as a bluff body invested by the oblique wind resulting from the combination of free-stream and rotor slipstream.

Figure 6 shows the ratios between the whole aircraft aerodynamic force components (in Z and X directions) and the estimated aircraft weight. In particular, Figure 6(a), 6(c) and 6(e) illustrate the ratio between the aircraft lifting force and its weight for different flight conditions and wing configurations. The dashed line in the pictures in-

dicates the horizontal flight equilibrium condition where the ratio between the aerodynamic vertical force component and the aircraft weight assumes a value equal 1. It has to be observed that during the tests the thrust required to fly in horizontal flight was never achieved due to the rig limitations. Nevertheless the trend of the ratio between total vertical force component and the aircraft weight, as a function of the rotor vertical force coefficient, appears quite clear moving toward the aircraft horizontal flight condition. As already explained, the fuselage contribution was not included in the Z force component since it was assume negligible. On the other hand, Figure 6(b), 6(d) and 6(f) show the ratio between the horizontal force component and the aircraft weight. Such a ratio represents the aircraft horizontal acceleration in terms of g (this acceleration is intended in the free-stream direction so that a negative value of the ratio between the horizontal force component and the aircraft weight means a positive forward acceleration).

The results reported in Figure 6 demonstrated that the possibility to rotate the wing and nacelle independently of each other was a fundamental feature to allow the aircraft to convert from helicopter to aeroplane mode. Furthermore, experimental results suggested that the wing rotation would anticipate the nacelle rotation when passing from hovering to aeroplane flight so that the beneficial effects produced on the lift component were not compromised by a strong drag increase.

5 CONCLUSIONS

In the present work the aerodynamic interference between wing and rotor of a new tiltwing aircraft employing the partial tilting wing solution was investigated in the initial stage of the transition manoeuvre that allows the aircraft to convert from helicopter to aeroplane mode. For this purpose, a wind tunnel half-span model reproducing one half-wing and its rotor was tested in the open test section of the Politecnico di Milano Large Wind Tunnel. Experimental data gathered during the test campaign allowed to describe the effects of the aerodynamic interaction between wing and rotor on the aircraft performance.

Experimental measurements revealed that the wing behaviour was influenced by the rotor wake and depended on the flight condition considered. It was observed that the outer wing deflection remarkably increased the wing lift and sometimes its drag. As a consequence, good wing aerodynamic performance (high lift and small drag forces) could

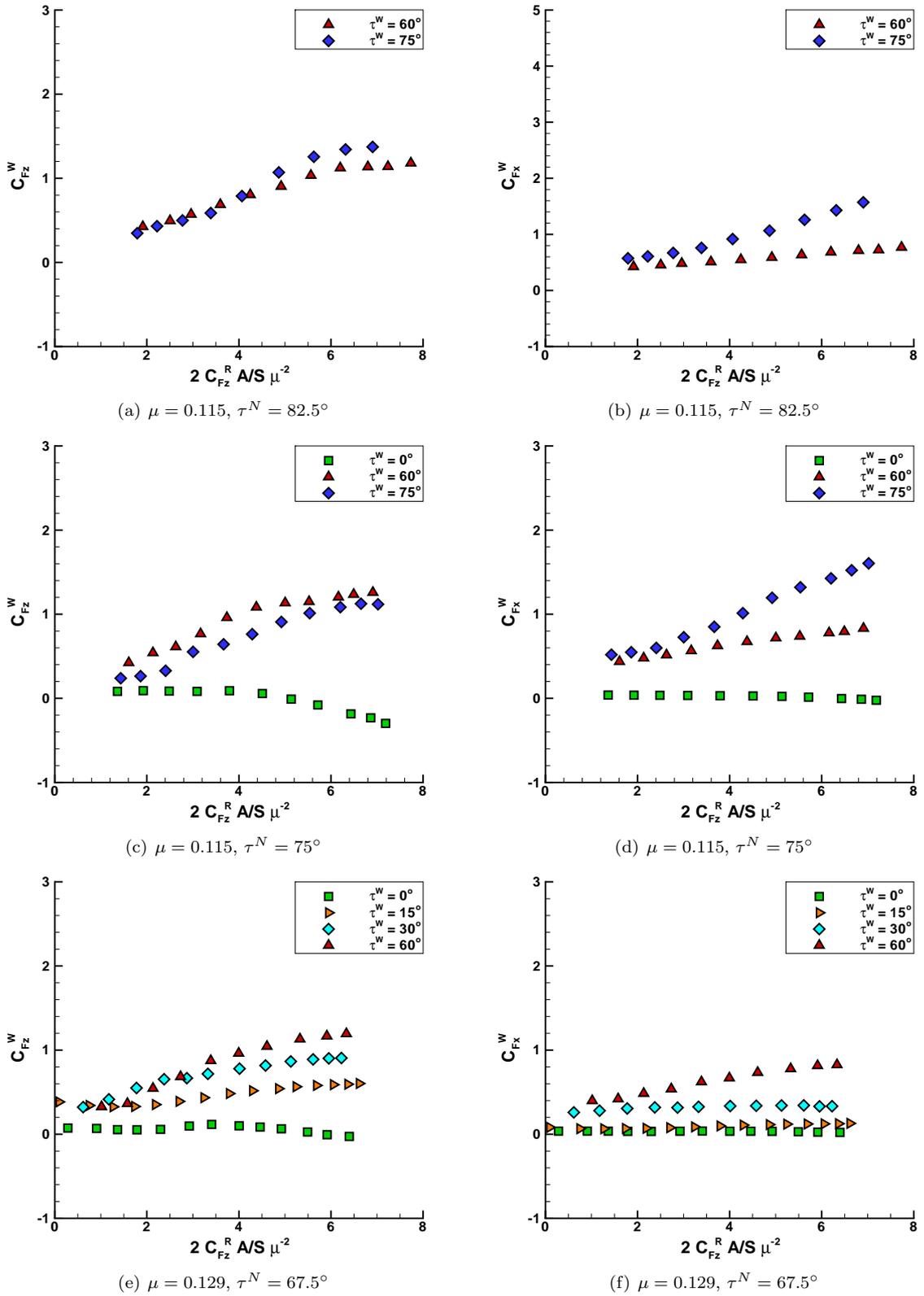
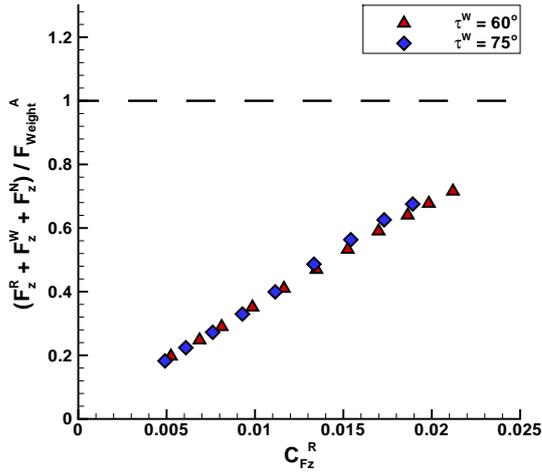
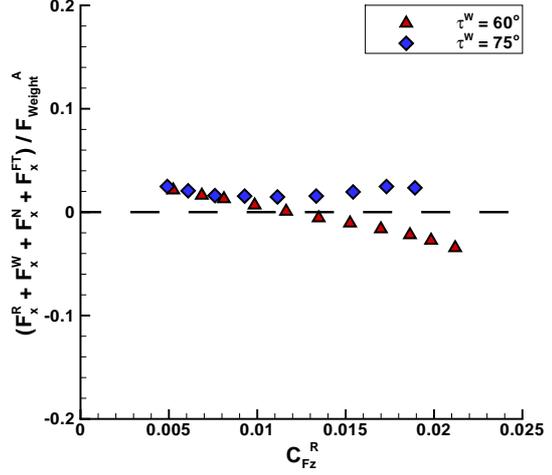


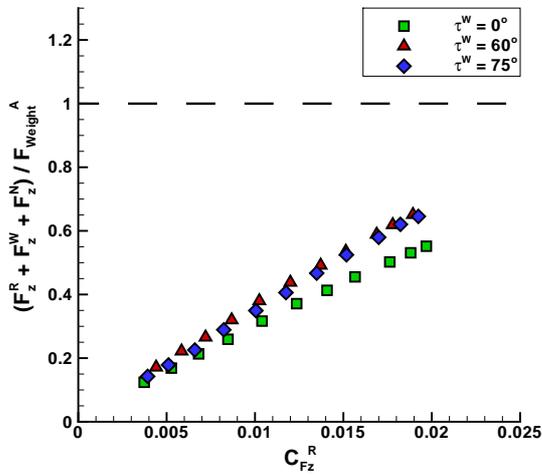
Figure 5: Wing airloads as function of rotor vertical load. Comparison between several wing configurations in different of the transition manoeuvre.



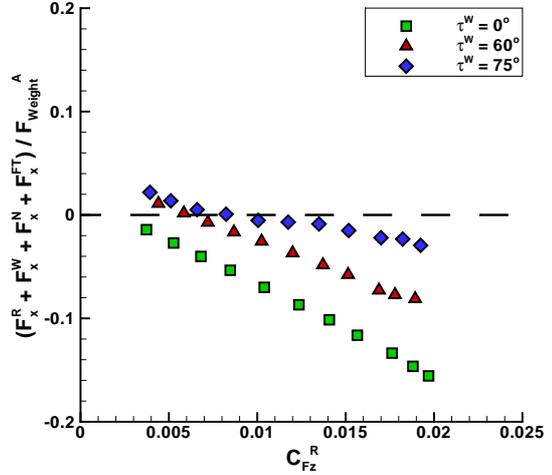
(a) $\mu = 0.115, \tau^N = 82.5^\circ$



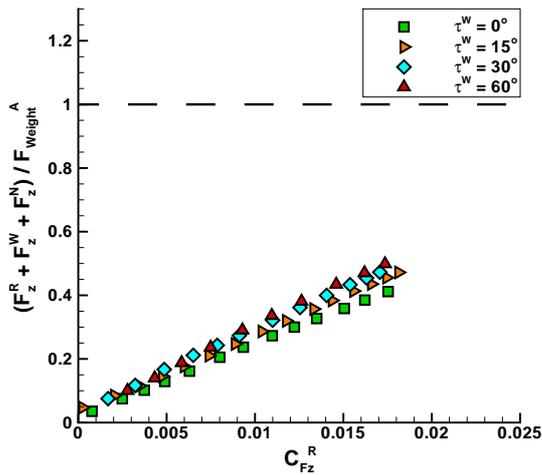
(b) $\mu = 0.115, \tau^N = 82.5^\circ$



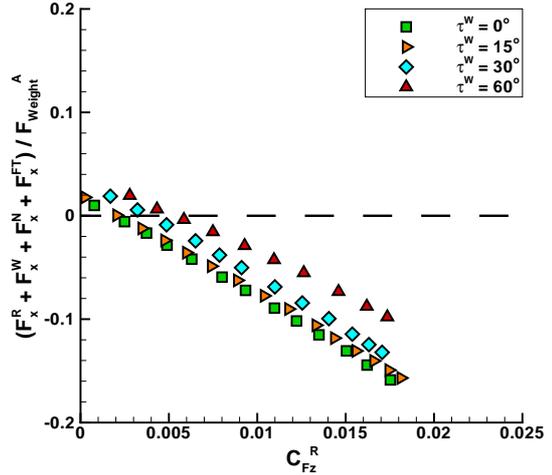
(c) $\mu = 0.115, \tau^N = 75^\circ$



(d) $\mu = 0.115, \tau^N = 75^\circ$



(e) $\mu = 0.129, \tau^N = 67.5^\circ$



(f) $\mu = 0.129, \tau^N = 67.5^\circ$

Figure 6: Aircraft performance as function of C_{Fz}^R . Comparison between several wing configurations in different of the transition manoeuvre.

be achieved setting proper wing configurations during the conversion manoeuvre.

The analysis of the aircraft performance clearly demonstrated the effectiveness of the partial tilting wing solution. Although such solution leads to a greater mechanical complexity, test results illustrated that it was fundamental for the aircraft flight dynamics during the transition manoeuvre. Furthermore, the possibility to rotate the outer wing independently from the nacelle allowed the aircraft to continuously adapt its configuration during the conversion looking for the best wing aerodynamic performance.

The database gathered during the experimental tests is accessible on request to the authors to be useful for numerical validations.

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