STUDY OF THE LOW SPEED CHARACTERISTICS OF A TILTROTOR

André Desopper
Olivier Heuzé
ONERA
Salon de Provence, France

Vincent Routhieau
Sébastien Baehrel
EUROCOPTER
Marignane, France

German Roth
EUROCOPTER DEUTSCHLAND
Ottobrunn, Germany

Wolfgang von Grünhagen
DLR
Braunschweig, Germany

Henk Haverdings
NLR
Amsterdam, The Netherlands

Abstract

This paper describes the studies performed to understand and to model the hover and low speed characteristics of a Tiltrotor. The work presented is part of the RHILP project sponsored by the EUROPEAN UNION under the 5th FWP programme and has been carried out through a combined effort of European research organisations and helicopter industries. The main results presented concern wind-tunnel tests performed to study some of the main hover and low speed wing/rotors interaction phenomena (wing download, fountain flow effect, ground effect), simplified models developed and included in a flight mechanics code to be used for piloted simulations and the validation of these models by comparisons with the test results.

Introduction

Research on Tiltrotor aircraft is increasing in Europe, the main goals being to propose a solution for the growing problem of airport congestion and to open a new perspective in the aeronautical market of the coming years. In March 2000 the three years Project RHILP (Ref 1) ("Rotorcraft Handling, Interactions and Load Prediction"), sponsored by the EUROPEAN UNION under the 5th FWP programme, was launched. Its main objective is to address important topics related to Tiltrotor such as Handling Qualities criteria, aerodynamic interactions and structural transient loads. Piloted simulations will be conducted on the Eurocopter simulator in Marignane (France) for the final validation of the developed models and requirements.

Work-package 2 of the RHILP European project deals with the hover and low speed characteristics of the Tiltrotor when flying in helicopter mode (nacelle angle with horizontal reference between 80 and 100° and speeds up to 100 kts approximately). In these conditions a Tiltrotor has specific characteristics and phenomena such as a strong aerodynamic interaction between the rotors and the wing generating wing download and fountain flow effects both penalising in terms of hover performance and payload capability . The most important phenomenon is due to the wake of the two rotors impinging the wing below and therefore generating an important download. A part of the flow field on the wing is turned in the spanwise direction. At the Tiltrotor centreline, the spanwise flows from both wings meet and turn upward in what is called the fountain flow effect which contributes to the total download (Fig 1). The presence of the wing and the recirculation zone modify also the rotors induced velocities and thus, the Tiltrotor performance. When the Tiltrotor is close to the ground, ground effect modifies all these phenomena, in particular the fountain flow effect due to the flow on the ground decreases the wing download (Fig 2). One of the most important factor in download reduction is the wing flap deflection. More detailed qualitative and quantitative information about these phenomena can also be found in (Ref 2-10).

In order to better understand and model some of the main phenomena, the following studies have been performed:

- Tests have been conducted in the Eurocopter wind-tunnel in Marignane with

a modular tiltrotor mock-up (Fig 3 and 4) that allows testing of the isolated rotor and of a half span model with or without a symmetry plane. All these tests have been performed in and out of ground effect and for a large sweep in wing flap deflection;
- development and validation of simplified models that have been included in the Eurocopter flight mechanics code (Ref 11) to be used for piloted simulations.

This paper describes the wind-tunnel test performed, the main results obtained, the simplified models developed and their validation by comparison between computed and experimental results.

Wind-tunnel test

The main investigation area of these tests regards the aerodynamic interactions between rotors and wing, in helicopter mode, in hover and low speed conditions (nacelle angle between 80° and 100° and forward speeds up to 90 kts). Indeed, even if the main phenomena encountered (wing download, fountain flow effect…..) are already known, very few related experimental data are available in Europe. That is why tests have been conducted, using a powered model for three different configurations:
- **an isolated rotor**, used to measure performance characteristics with zero and non-zero forward speeds;
- **a half-span model** (starboard side) with one rotor, a nacelle, a half-span wing and a half-fuselage set on an image plane: this configuration has been used for hover and forward flight tests;
- **a rotor + wing model** with one rotor, a nacelle and a half-span wing, used to investigate the effect of the fountain flow phenomena on rotor performance and on wing download (through comparison with half-span tests).

Wind Tunnel
These tests have been performed from December 2001 to March 2002, in the Eurocopter wind tunnel facility located in Marignane (Fig 3). It is an Eiffel type wind tunnel with semi-guided air return. The test section is a circular open section, of 3m diameter. Airspeeds up to 45 m/s can be achieved, which was sufficient for the low speed tests considered here.

Model characteristics
The model used is shown on Fig 4. Its main characteristics are the following:

Half-Span (rotor tip to symmetry plane) 1.589 m
Length (from nose to rear end) 2.264 m
No tail surfaces
Rotor diameter 1.4 m
Number of blades per rotor 3
Operating rotor speed 1364 rpm
(i.e 100m/s blade tip speed)
Rotor solidity 0.103

The fully articulated rotor is driven by a 4 kW electric motor, located at the starboard side of the nacelle and cooled by pressured air. The gearbox and the rotor hub can be manually tilted up to 10° forward or rearward to simulate ±5° or ±10° nacelle tilting. The wing has a span of 0.630 m and a chord of 0.308 m. A manually adjustable flap of 0.100 m (33% of the wing chord), is set along the entire span of the wing. It can be set to any angle between 0° and 80° (for most tests cases, 10° steps have been used). To enable correct loads measurements, no contact has been allowed between the nacelle and the wing, as well as between the wing and the half-fuselage. No tail element (fin, horizontal stabiliser….) has been considered.

Model set-up and measuring equipment
The model has been divided into three parts:

- The rotor, the nacelle and the engine, supported by the main wind tunnel mast
- The wing alone supported by a second mast
- The half fuselage and an image plane fixed on the ground of the wind tunnel.

Two balances have been simultaneously used during this campaign: a three components (X, Z, M) balance to weight the "rotor + motor + nacelle" system, and a six components balance to measure wing loads. Rotor torque was captured by a strain gauges bridge located on the rotor shaft. The rotor has also been instrumented with a blade displacement sensor and a topper for rotor flapping and rotor speed measurements. A displacement sensor has been set on each control rod for pitch measurements. Different "safety measurements" devices were used and their signals displayed in real time, such as motor temperature probes or accelerometers located near the rotor head.

Using collective and cyclic pitch, the rotor has been trimmed, for a given advance ratio, to simulate calculated X and Z efforts, the lateral flapping being set to zero. All tests have been performed with zero attack, sideslip and bank angles.

Preliminary tests

Most of the test rig equipment, never used in such a configuration before, required a significant calibration effort. Moreover, because of the low balance stiffness, two dampers have been added in order to prevent dynamic instabilities. . Both dampers have been linked to the nacelle using aluminium rods (Fig 4), one along the longitudinal axis and one along the transversal axis. The influence of these dampers, i.e. the loads going through the rods during the tests, has been measured thanks to strain cells placed on each rod, the latter being linked to the damper and the nacelle by ball-joints.

Hover tests

Three main configurations have been investigated during this campaign: an isolated rotor configuration, a rotor and wing configuration and a half-span configuration (rotor, nacelle, wing, half-fuselage and image plane). For each of the two last configurations, the influence of different parameters on wing download has been investigated, such as rotor thrust, wing flap setting, lateral flapping, nacelle tilting, distance between rotor disc and wing. The comparison of half-span and rotor + wing configurations has enabled to quantify the fountain flow effect on rotor performance and on wing download. Each configuration has been tested "Out of Ground Effect" (Z/R=3.0) and for two different conditions "In Ground Effect " (Z/R=1.7 and 1.1). For each test case, a complete polar has been obtained (C_T from 0 to 0.016).

Forward flight test

Most of these configurations and parameters have also been investigated in forward flight, for three different wind tunnel speeds: 7.0, 14.0 and 21.1 m/s, which corresponds to 30, 60 and 90kts for a full scale aircraft. Some tests have been performed with the rotor stopped (blades removed), in order to capture the lift and drag characteristics of the nacelle and the wing. These tests have also permitted, through a comparison with tests with the rotor operating to capture respectively the effect of the forward speed and the effect of the rotor downwash on wing loads.

Wind-tunnel test results
Download on the wing

The results presented in this section focus on the download at the wing produced by a strong aerodynamic interaction with the rotor in hover and low speed forward flight. With nacelle angle set to 90° degrees (helicopter mode) following effects have been investigated at different wing flap settings and rotor thrust levels:

- ground effect
- fountain flow effect
- rotor to wing distance
- lateral flapping of rotor disc

The download to rotor thrust ratio (DL/T) plotted in the following figures is normalized by the value obtained for

- Ct=0.012 or 0.008 depending on the figure considered,
- zero wing flap setting,
- Out of Ground Effect (OGE),
- half span configuration and
- the nominal rotor to wing distance of 0.44R.

Download evolution in Hover

Figures 5 and 6 illustrate the download evolution for the half span model as a function of rotor thrust and wing flap setting in hover out of ground effect. With increasing thrust the downwash velocities in the inboard portions of the rotor wake are decreasing relative to the outboard portions, as shown by downwash velocities measurements performed on V-22A rotor [2]. As the major contribution to the download is due to the inner part of the rotor, the decrease of the download velocities in the outer part of the wing causes a decreasing download to thrust ratio (Fig 5). Wing flap reduces significantly the download up to an optimum setting of about sixty degrees (Fig 6).

In the (rotor+wing) configuration - that means without symmetry plane - the fountain flow effect does no longer exist. This phenomenon increases the download at the wing especially for low flap settings (Fig 7).

A beneficial effect of operating the aircraft in vicinity of ground is a decrease of wing download due to a rotor wake generating an upwash below the wing (Fig 8). The minimum value of download in ground effect (IGE) at Z/R=1.114 - which means almost wheels on ground - is reduced to less than 20% of the OGE value. At the same time the minimum is slightly shifted by about ten degrees towards lower flap settings with decreasing distance to ground.

Tilting the rotor disc towards the wing tip intensifies the negative effects (Fig 9), whereas this influence is less important when operating at optimum wing flap setting. For wing flaps equal to zero an asymmetry in download between inboard and outboard disc tilt exists, which is more dominant in IGE condition.

The variation of the rotor to wing distance in a range between 0.37R and 0.47R in rotor+wing configuration (Fig 10) shows no significant benefit for the download especially at the optimum flap setting of sixty degrees and nominal thrust levels.

Preliminary results in low speed forward flight
The results presented for forward flight have preliminary status, as the evaluation is not yet completely finished.

In forward flight the tests have been performed with a longitudinal rotor blade flapping between zero and three degrees nose down whereas in hover it is always trimmed to zero. The rotor thrust considered is Ct=0.012. Tests were performed at thirty, sixty and ninety knots with and without rotating rotor to be able to extract the pure rotor-to-wing interaction effects.

Figures 11 and 12 illustrate the influence of wing flap setting and ground distance from hover to sixty knots for the half span model. For zero flap setting the download decreases up to sixty knots in OGE condition (Fig 11). For all other flap angles the situation is different. At sixty knots the download is approximately constant for flaps between forty and eighty degrees and nearly double the value as for zero degrees. No physical explanation has been found yet to explain this behaviour. However at thirty knots the optimum flap setting seems to be close to forty degrees. The download clearly deteriorates at higher flap angles.

The significant upwash effect during hover in ground effect with sixty degrees flap angle is cancelled out at thirty knots forward speed (Fig 12). Zero flap setting seems to be the best choice at sixty knots also in IGE condition, if regarding only this download problem.

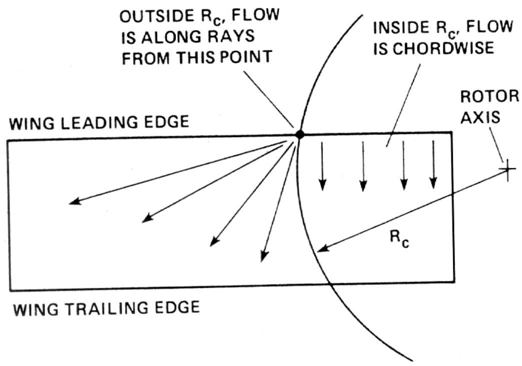
Wing download models

Wing download in hover with 90° nacelle tilt :
This model of the wing download calculation is based on visualisation made with wool tufts during the wind tunnel campaign and on the calculation exposed in Ref. 2. The flow over the wing is separated into two regions as shown on the scheme below (from Ref. 2):

- Near the wing tip, the flow is in the chordwise direction,
- Near the wing root, the flow is mainly in the spanwise direction.

The limit of the two regions is at Rc from the rotor axis. Rc is a function of rotor thrust coefficient (Ct) and increases with Ct.

The download calculation in hover is based on the drag force of the wing under –90° angle of attack and with the rotor induced velocity at the wing level for the direct effect (rotors wake impinging on the wing). The download part due to the fountain flow effect is calculated by applying momentum theory to the spanwise part of the flow over the wing.



Flow on the wing (From Ref. 2)

This method had been applied for a V-22 configuration. Induced velocities in hover at the wing level have been taken from Ref. 3. The wing airfoil drag coefficient at –90° angle of attack has been estimated from Ref. 4. The resultant wing download evolution with the rotor thrust is presented on Fig. 13. The part of the fountain flow effect on the wing download is between 10 and 17% depending on the Ct value which is consistent with published results and with the ones obtained in the present tests (Fig 7).
This approach has been used also to study the effect of lateral flapping on the wing download as presented on Fig 14. These results have to be compared with the test results of Fig 9.

Models implemented in inhouse code
Simplified models have been developed and included in the Eurocopter flight mechanics code (Ref 11) to compute the wing download in and out of ground effect. These models have to be simple in order to be used not only for off-line simulation but also in real time for piloted simulations.

Wing download model in hover
The download model for the tilt-rotor in hover and in helicopter mode (nacelle at 90°) is

based on two curves obtained either through simplified calculations or published experimental results giving the evolution of :

- the download with rotor thrust at a given wing flap angle (Fig 13)
- the download divided by the download at 0° flap angle with the flap angle (Fig 15).

Knowing the rotor thrust and the wing flap setting, the download is then computed by interpolation of the 2 previous curves (Fig 16).

Influence of the ground effect on the download

Wing download evolution in ground effect is obtained by using published data from tests of small-scale Tiltrotor model (Fig. 17 from Ref 5).

These data gives the evolution of the download with the height above the ground; they show that the download decreases when the height above the ground decreases and can even be negative (lift) for height-to-radius ratio below 1~1.25. This evolution is used to modify the download computed out of ground effect with the Tiltrotor height above ground. The effect implemented in the Eurocopter flight mechanics code corresponds to the results of Fradenburgh (Ref 10).

Influence of the forward speed and nacelle angle

The model used in hover has been extended to take into account both the forward speed and the nacelle tilt angle. Two approaches have been used:

- Model 1 :
  a simple evolution of the download with the forward speed (Vh) and the nacelle tilt angle (Dnac) is used, assuming that the download will be completely cancelled at a forward speed of 60 kts :

$$DL = DL_{Vh=0,\,Dnac=90°}.\left(1-\sin^2\left[\frac{\pi.Vh}{2.Vtran}\right]\right).\sin(Dnac)$$

  Where Vtran is the speed limit at which there is no longer rotor/wing interaction. (Vtran=30m/s).

- Model 2 :

$$DL = DL_{Vh=0,\,Dnac=90°}.\left(\frac{V_{im}}{V_{i0}}\right)^2.\sin^2(Dnac).\eta$$

  Where V_{im} is the mean induced velocity at the rotor disc, V_{i0} the theoretical induced velocity in hover, and η a coefficient between 0 and 1 characterising the wing chord area in the rotor wake.

The resulting download force is parallel to the nacelle direction.

More detailed description about these simplified models can also be found in Ref 12 as well as for simplified models developed to have the influence of the wing on the rotor in term of blocking effect and re-circulation effect. These 2 effects go in opposite directions and almost compensate one another.

Models validation

The simplified models described before have been implemented in the Eurocopter flight mechanics code. Some calculations have been performed before the tests in the same conditions that the wind-tunnel tests and comparison between these “pre-tests” computed results and experimental results are presented on Fig 18 to 22.

Fig 18 presents the evolution of the download in hover divided by the rotor thrust versus rotor Ct for different wing flap settings. Both the evolution of the download with the rotor thrust and the download decrease with the wing flap setting up to 60° are relatively well predicted. However the calculations slightly over-predict the wing download level for 0° of wing flap setting.

Fig 19 compares the evolution of the download in hover with the wing flap setting. The decrease of the download with the flap setting is relatively well predicted, however the effect of the flap is over-predicted in term of minimum level of wing download and the optimum flap angle value obtained during the tests is smaller than the one taken for the calculations.

Fig 20 shows the influence of the ground effect on the wing download in hover with a slight under-estimation of the ground effect in the calculations compared to the test results.

The results from the 2 models are compared with the test results on Fig 21 and 22 for the evolution of the wing download with the forward speed out of ground effect (Fig 21) and in ground effect (Fig 22). Out of ground effect the model 2 has a tendency to under-predict the decrease of the wing download with the speed and for model 1 the speed at which the download is equal to 0 is slightly too low. In ground effect the download evolution with the forward speed is quite well predicted with model 2.

The experimental data concerning the evolutions of the download in hover with rotor thrust at 0° flap setting (Fig 18) and with the flap setting (Fig 19) have been used to “adjust” the simplified models implemented in the Eurocopter flight mechanics code. Fig 23 and 24 present the comparisons obtained after these adjustments and they show very good comparisons.

Conclusion

This paper describes the work performed under the Work Package 2 of the European project RHILP ("Rotorcraft Handling, Interactions and Load Prediction") to study the hover and low speed aerodynamic interaction phenomena that are encountered on a tiltrotor aircraft (wing download, fountain flow effect, ground effect). The results presented concern :

- Wind-tunnel tests that have been performed in the Eurocopter wind-tunnel in Marignane with a modular tiltrotor mock-up for isolated rotor and half span model with or without a symmetry plane configurations. These tests being performed in and out of ground effect and for a large sweep in wing flap deflection. The results presented give the evolution of the wing download with the rotor thrust, the wing flap deflection and the forward speed.
- Simplified models that have been developed for the wing download prediction in hover and low speed including fountain flow and ground effects. These models have been implemented in the Eurocopter flight mechanics code to be used for piloted simulations.
- Validation of the models by comparisons between predicted results and experimental ones.

All the results presented concern quasi-static configurations and in these conditions the characteristics predicted by the interaction models that have been developed are in quite good agreement with the test results even if the increase of the wing download with the wing flap deflections in forward flight for flap deflection larger than 30° is not predicted by the simplified models considered here. The experimental database obtained through the tests is also very valuable to validate more sophisticated aerodynamics models such as CFD ones.

The flight mechanics code including the models presented in this paper is going to be used for the piloted simulations scheduled in the 4th workpackage of the RHILP project.

Other European projects are going on to study more sophisticated aerodynamic interaction models as well as other topics concerning advanced tiltrotor [13].

Acknowledgement

The authors wish to acknowledge the European Commission for the financial support of the RHILP Critical Technology Project (G4RD-CT-2000-00208) within the Fifth Research Framework Programme of the European Union.

REFERENCES

[1] Ph. Rollet: "*RHILP - A major step for European Knowledge in Tilt-Rotor aeromechanics and flight dynamics*", Aeronautics Days 2001, Hamburg, Germany, Jan 29 - 31, 2001

[2] F.F. Felker, J.S. Light, *"Rotor/wing aerodynamic interaction in hover"*, 42nd AHS Forum, June 1986

[3] F.F. Felker, D.B. Signor, L.A. Young, M.D. Betzina : *"Performances and loads data from a hover test of a 0.658-scale V-22 rotor and wing"*, NASA TM 89419, April 1987

[4] M.A. McVeight, W.K. Grauer, D.J. Paisley, *"Rotor/airframe interaction on tiltrotor aircraft"*, 44th AHS Forum, June 1988

[5] F.F. Felker : *"A review of Tilt rotor download research"*, 14th European Rotorcraft Forum, 1988

[6] M. Knight, R.A. Hefner "Analysis of ground effect on the lifting airscrew", NACA TN 835, 1941

[7] C.D. Coffen, A.R. George, H. Hardinge, R. Stevenson : *"Flow visualization and flow field measurements of a 1/12 scale Tilt Rotor aircraft in hover"*, NASA-CR-189456

[8] R.L. Marr, D.G. Ford, S.W. Ferguson : "Analysis of the wind tunnel test of a Tilt Rotor powered force model", NASA CR 137529, June 1974

[9] Anon. : *"Wind tunnel test of a powered Tilt Rotor performance model, Vol. V"* ,AFFDL-TR-74-62, October 1972

[10] E.A. Fradenburgh : *"Aerodynamic factor influencing overall hover performance"*, AGARD C.P. 111, September 1972

[11] B. Benoit, A.-M. Dequin, P.-M. Basset, B. Gimonet, W. von Grunhagen, K. Kampa *"HOST, a general helicopter simulation tool for Germany and France"*, 56th A.H.S. Annual Forum, Virginia Beach (US), May 2-4 2000

[12] O.Heuzé, S.Diaz, A.Desopper *"Simplified models for tiltrotor aerodynamic phenomena in hover and low speed flight"*, CEAS Aerospace Aerodynamics Research Conference, Cambridge (UK), 10-13 June 2002

[13] M.Cicalè, F.Nannoni, A.Pisoni, M.Allongue, P.Rollet, P.Hellio "The Aerodynamic Challenge of the European Advanced tiltrotor", CEAS Aerospace Aerodynamics Research Conference, Cambridge (UK), 10-13 June 2002

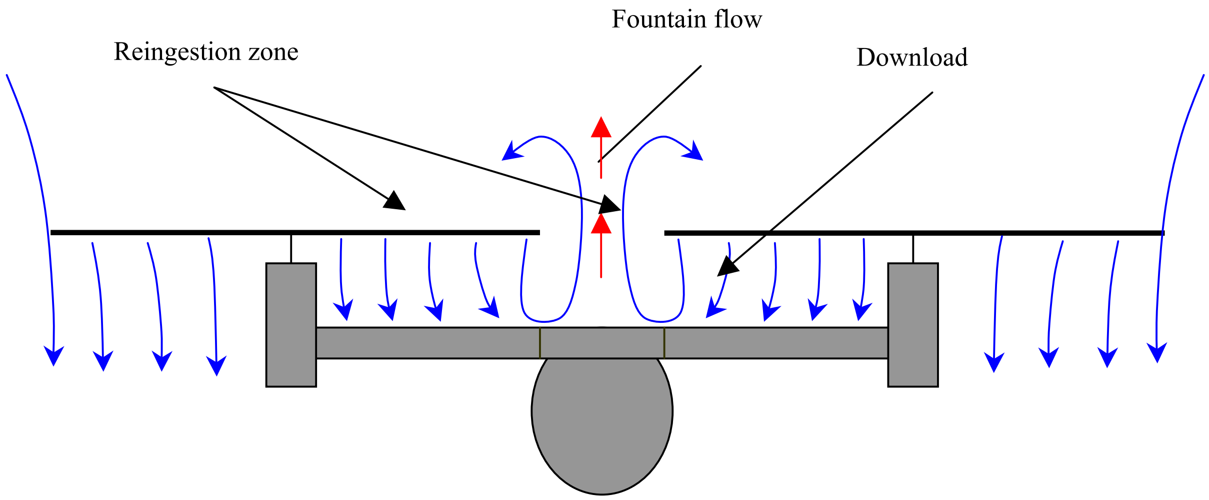


Figure 1 : Flow fields on Tiltrotor in hover

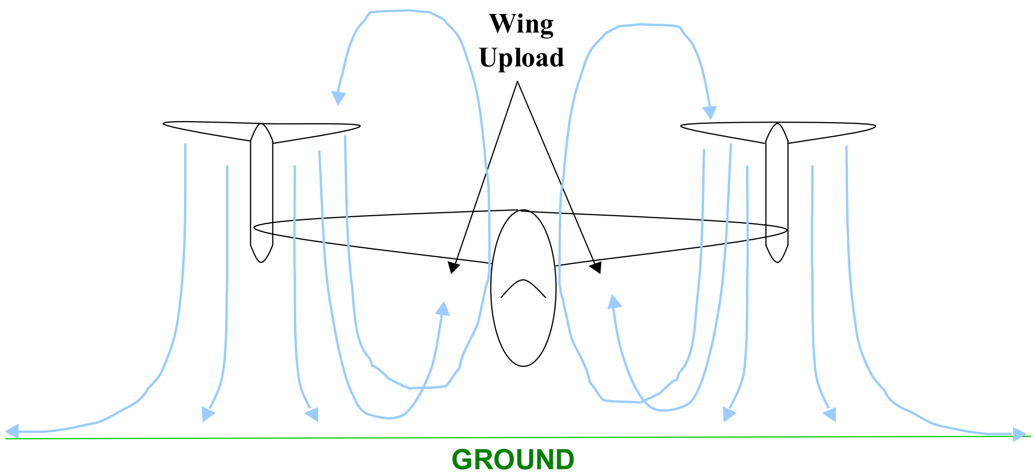


Figure 2 : Ground effect for a Tiltrotor in hover

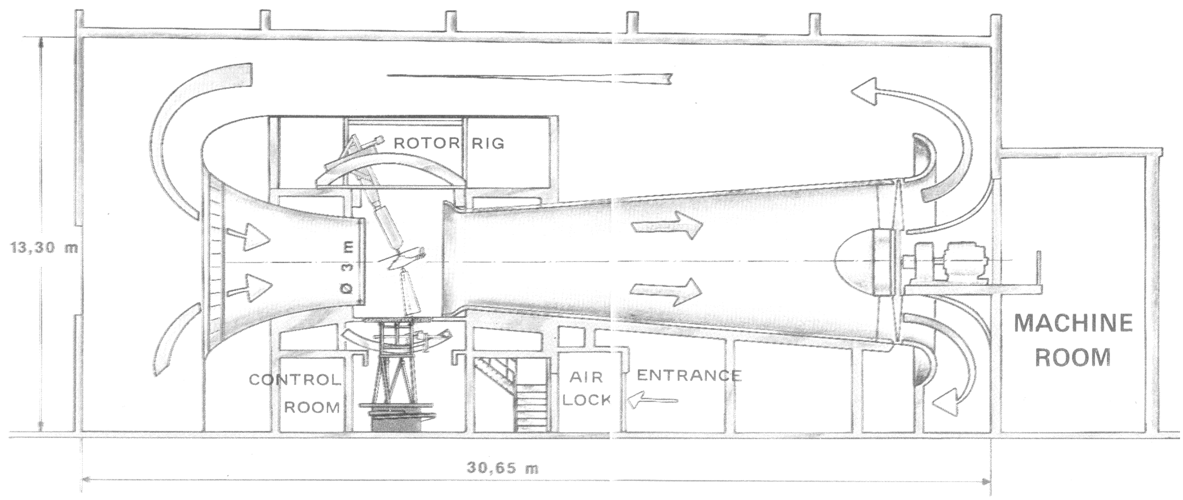


Figure 3 : Eurocopter wind-tunnel facility

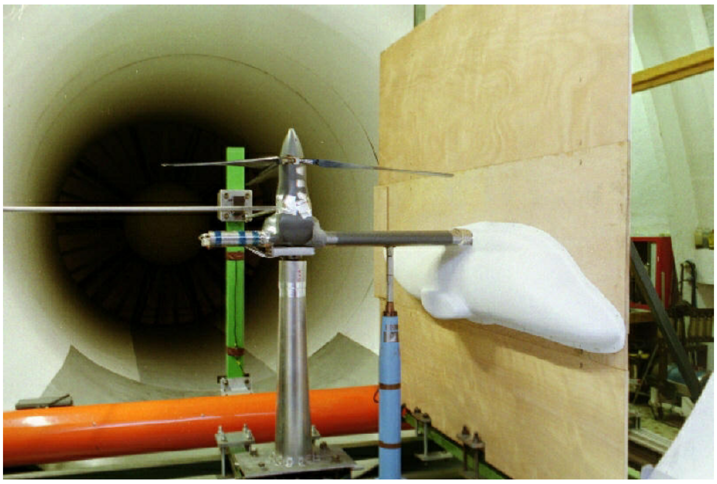


Figure 4 : Half-span configuration set-up

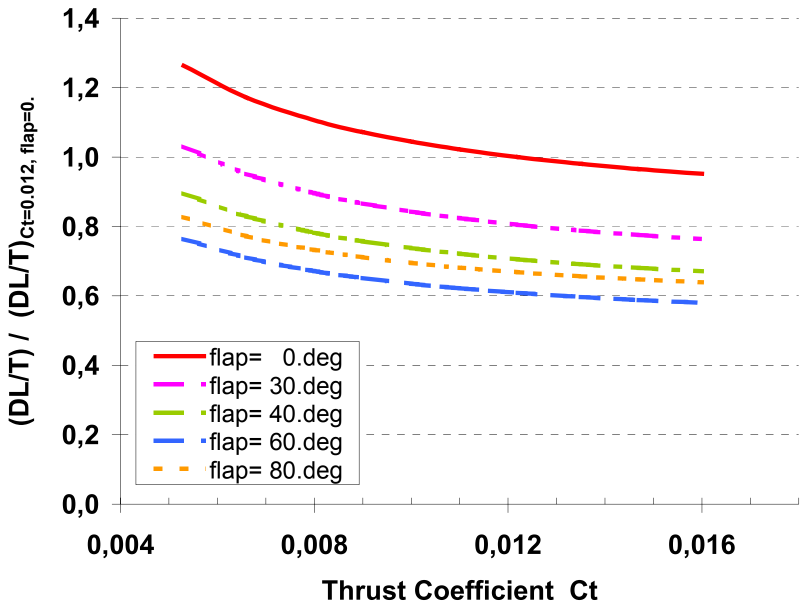


Fig 5 Influence of rotor thrust on download at different flap angles (OGE, half span model)

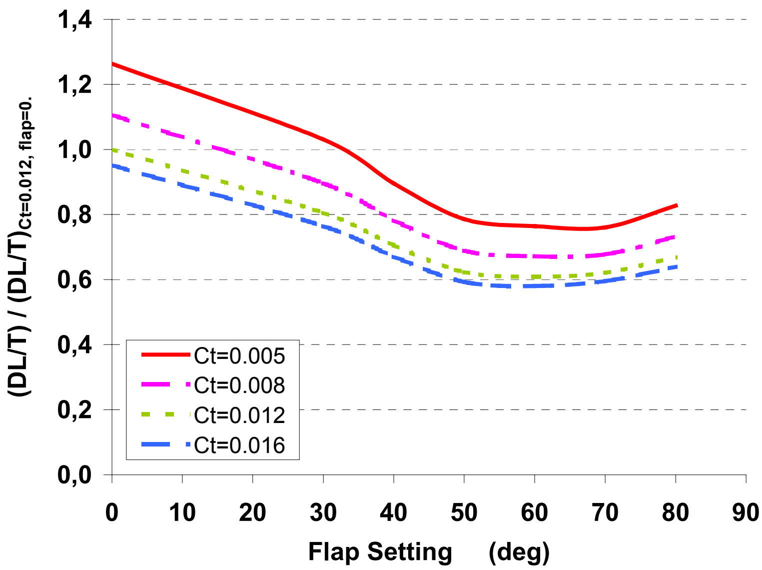


Fig 6 Download versus flap angle for different Ct (OGE, half span)

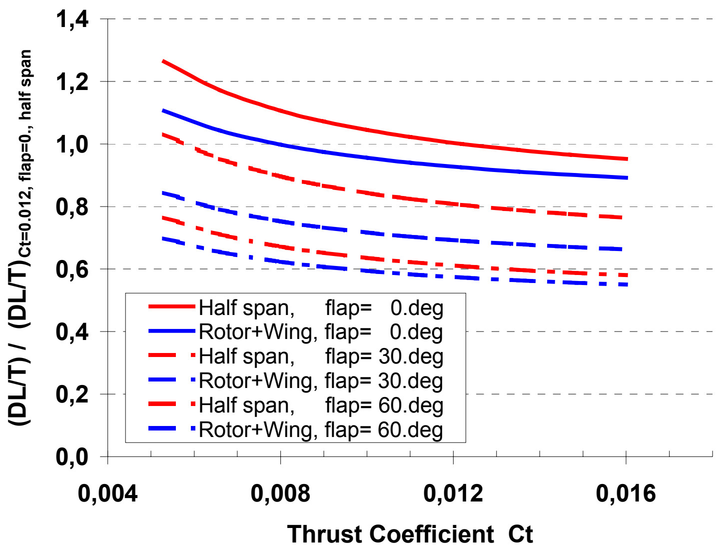


Fig 7 Influence of fountain flow effect for different flap angles (OGE, half span and rotor+wing model)

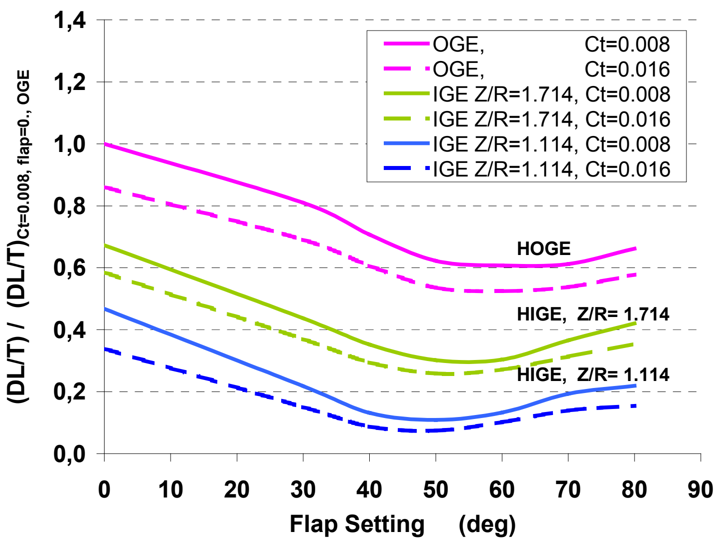


Fig 8 Ground effect on the wing download

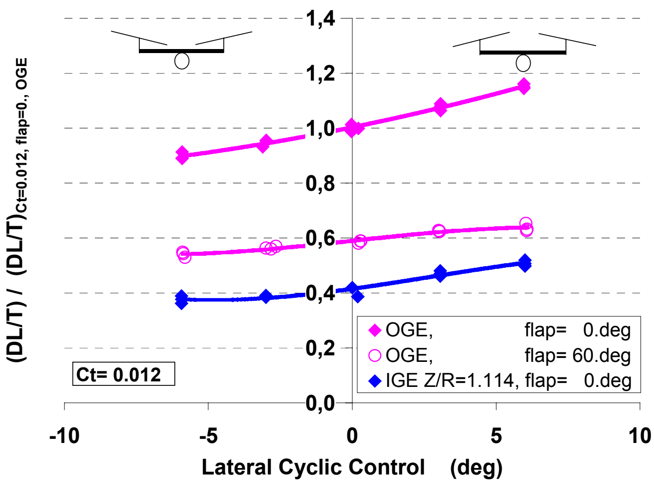


Fig 9 Influence of the lateral cyclic pitch on the wing download

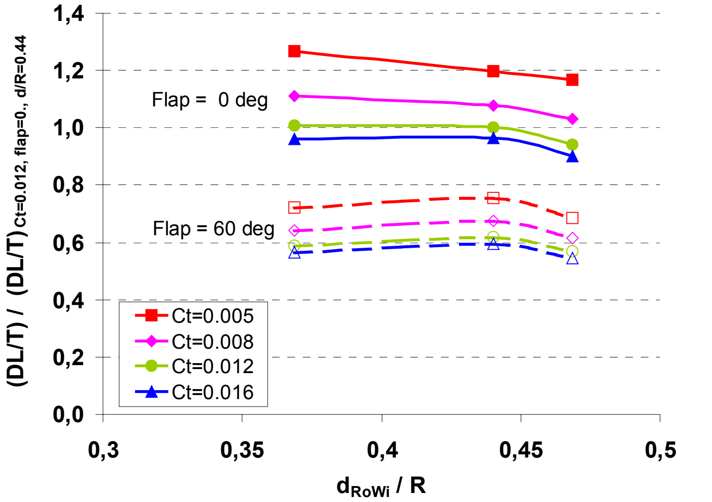


Fig 10 Influence of the rotor/wing distance on the wing download

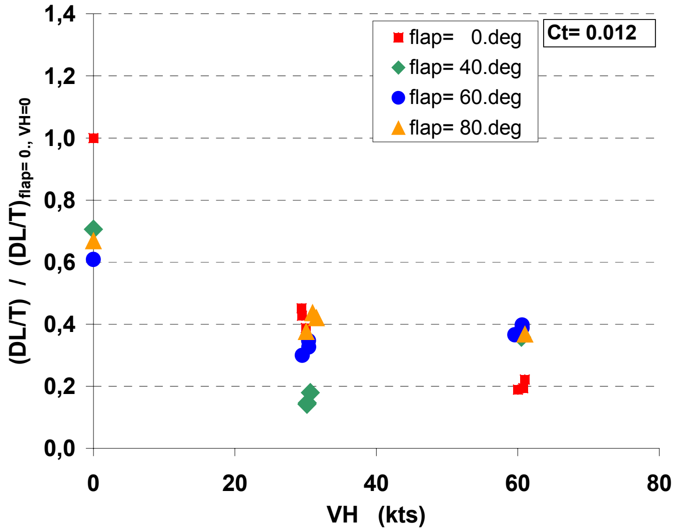


Fig 11 Influence of the forward speed on the wing download

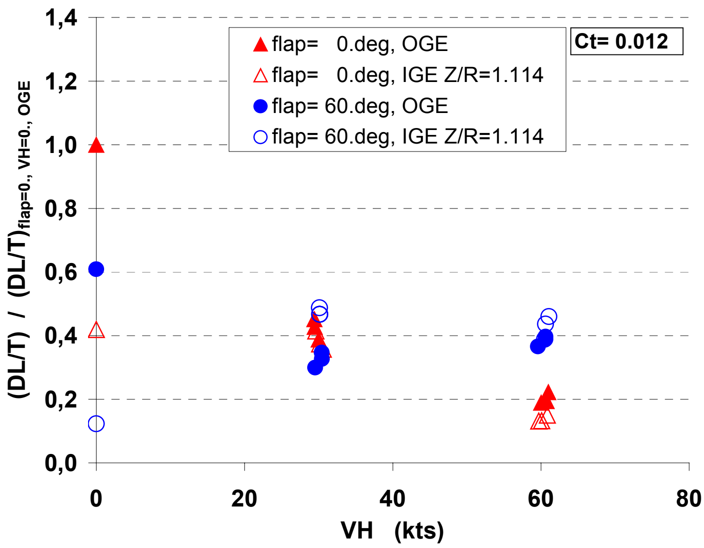


Fig 12 Influence of the ground effect on the wing download in forward flight

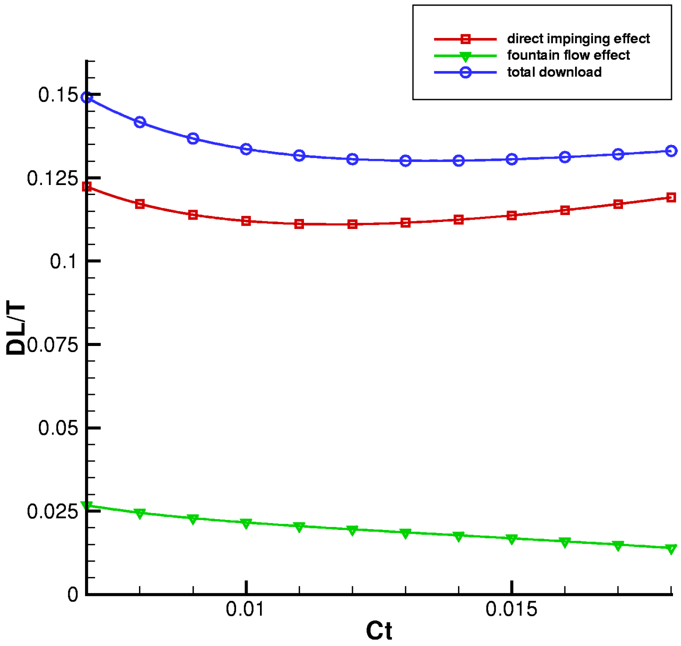


Figure 13 : Download at zero wing flap setting

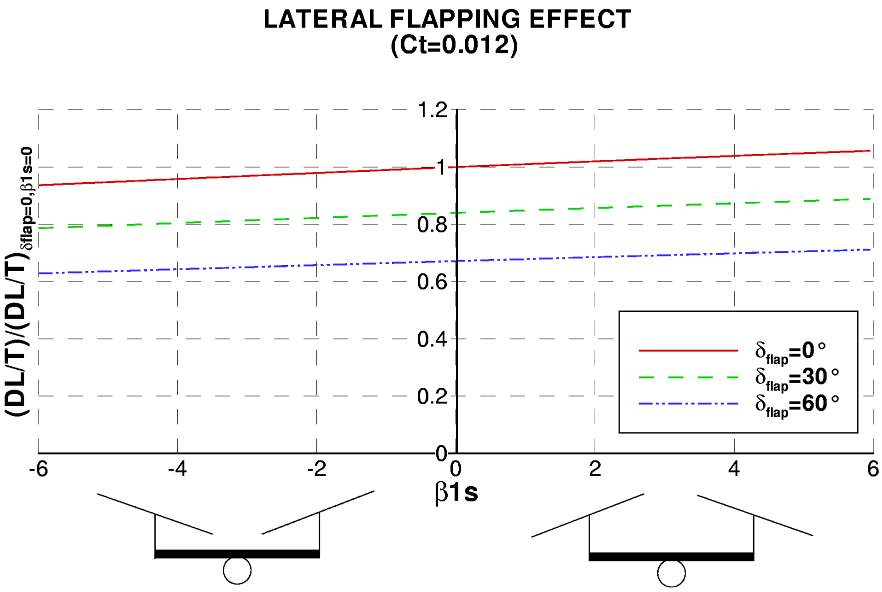


Figure 14 : Influence of rotor lateral flapping on the wing download in hover

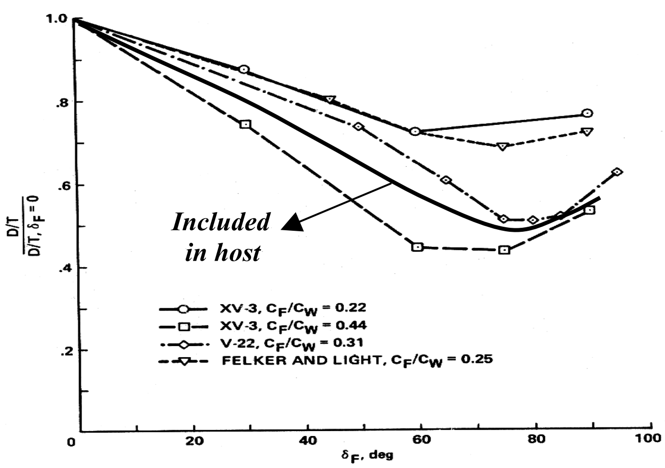


Figure 15 : Influence of the wing flap setting on the wing download in hover (From Ref. 5)

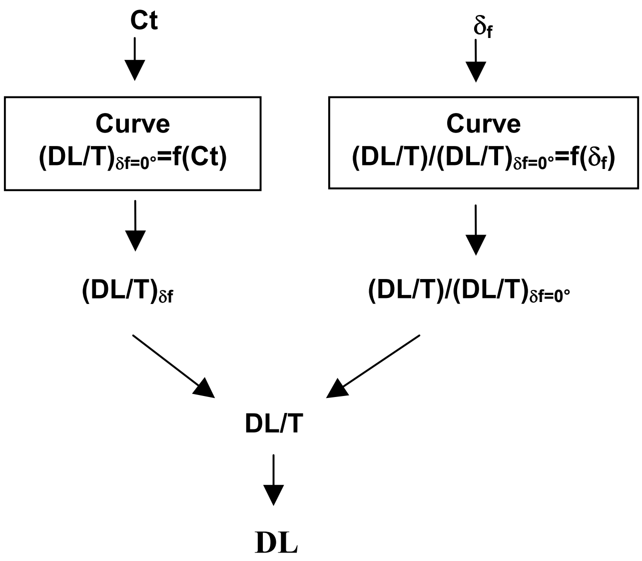


Figure 16 : Wing download calculation in hover

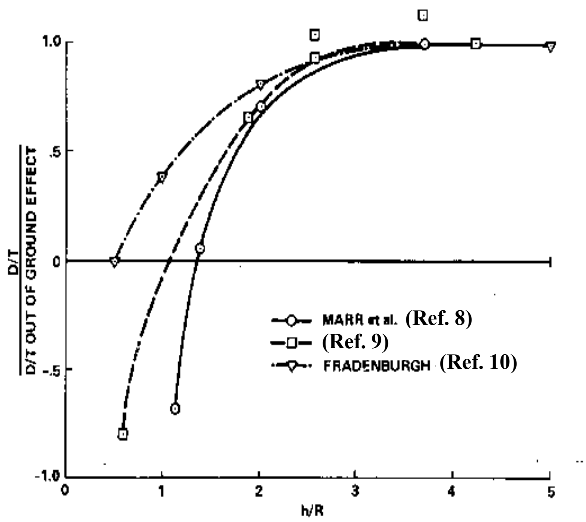


Figure 17 : Wing download evolution function of height above ground (From Ref. 5)

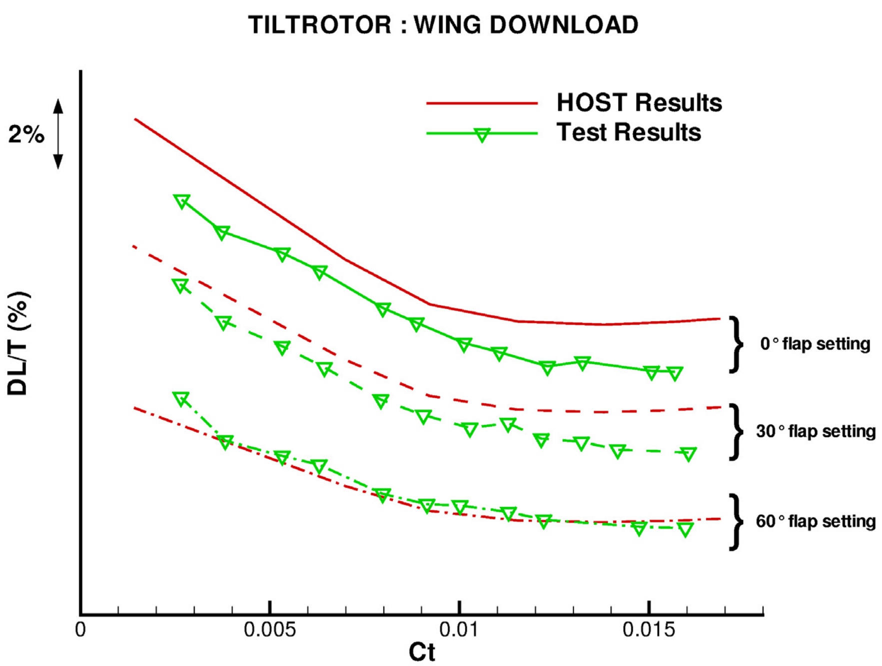


Fig 18 Comparison tests/calculation : Influence of the Ct on the wing download

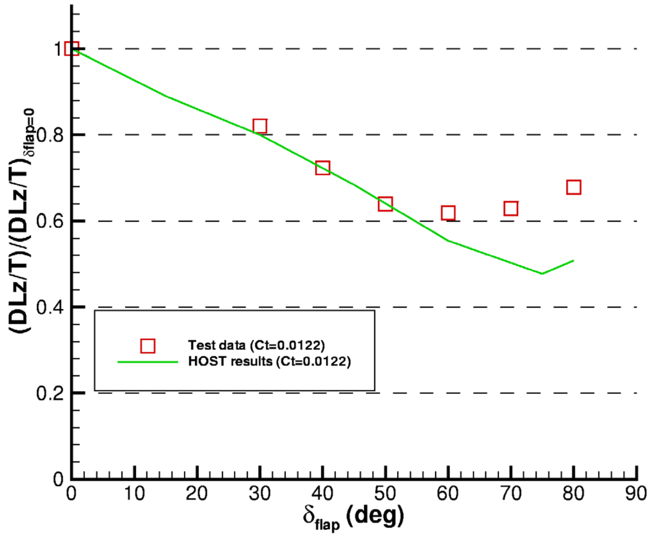


Fig 19 Comparison tests/calculation : Influence of the wing flap deflection on the wing download

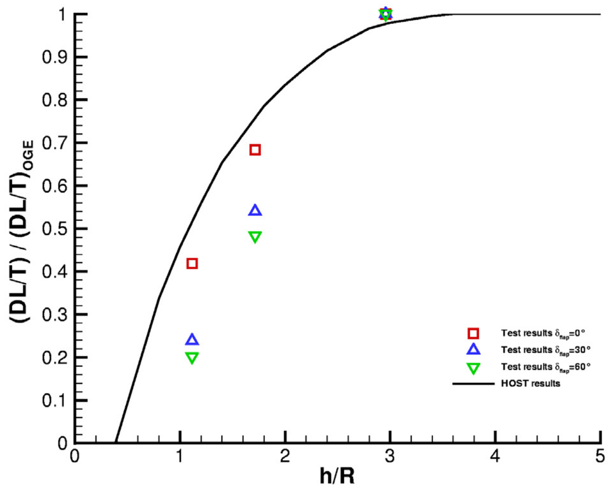


Fig 20 Comparison tests/calculation : ground effect on the wing download (Ct = 0.012)

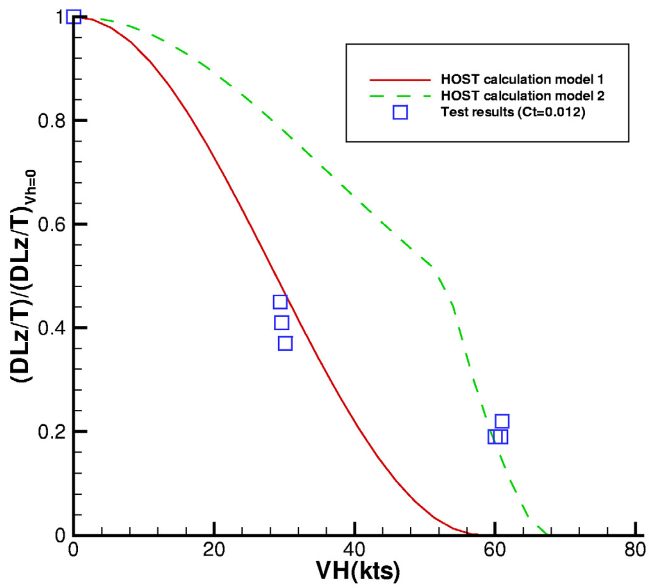


Fig 21 Comparison tests/calculation : wing download in forward flight OGE (wing flap = 0°)

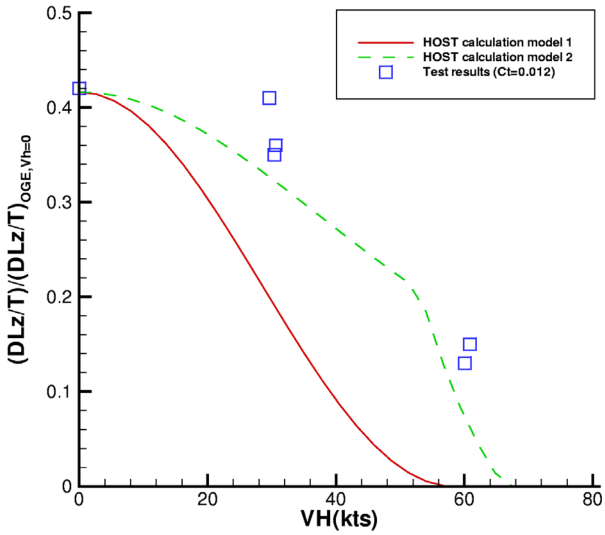


Fig 22 Comparison tests/calculation : wing download in forward flight IGE (Z/R=1.114, wing flap = 0°)

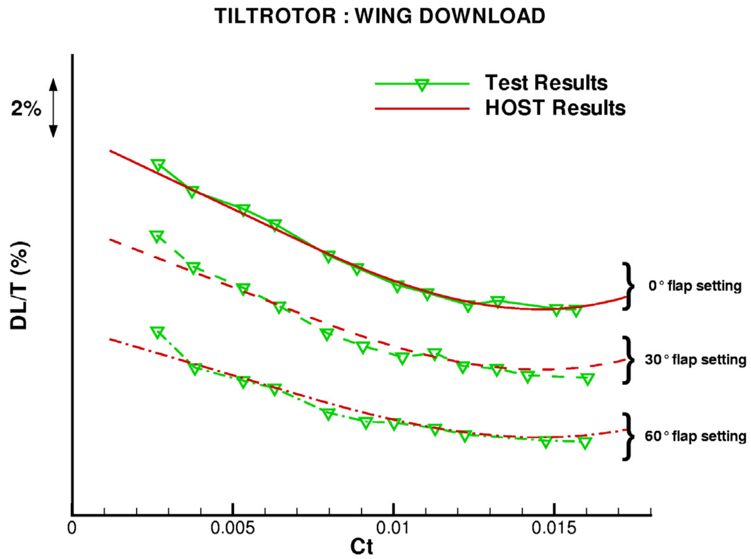


Fig 23 Comparison tests/calculation after models adjustment

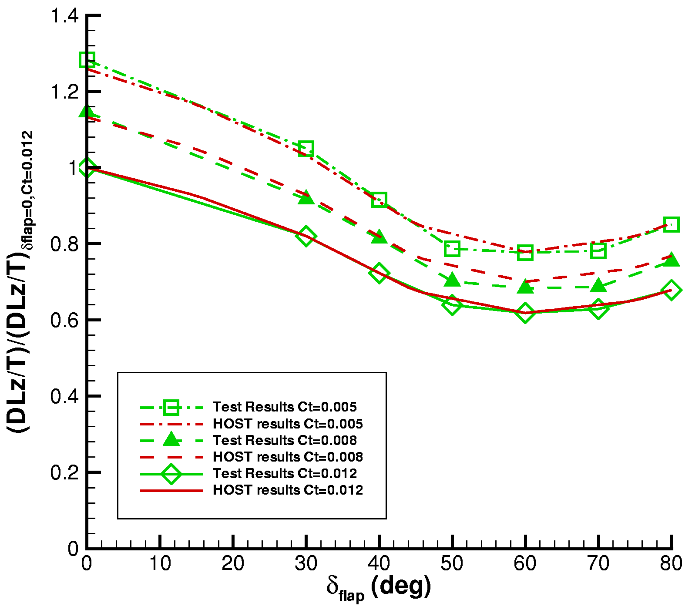


Fig 24 Comparison tests/calculation after models adjustment