Helicopter Ground Vortex
Comparison of Numerical Predictions with Wind Tunnel Measurements

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Abstract
In the framework of the Brite Euram project HELIFLOW, research activities were conducted aimed at knowledge acquisition in the area of interactional aerodynamics, validation of wind tunnel test technologies and verification of related theoretical tools. This paper describes the ground vortex activities performed in Task 3 of the project, which addressed the low speed phenomena of quartering flight. During sideward flight in ground proximity, the helicopter main rotor induced ground vortex influences the main and tail rotor inflow conditions and thus its performance. Wind tunnel tests were performed with a powered BO 105 model in the Large Low-speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW), see figure 1.

Figure 1 BO 105 model in DNW-LLF test section

State of the art airflow test techniques were applied to measure the ground vortex flow phenomena.
The in-house developed OUTWASH code was extended with several features for application within HELIFLOW. It was applied for pre-test calculations to refine the wind tunnel test matrix and to define the experimental set-up for the flow measurements by calculating the ground vortex locations.
Based on the test results obtained, an OUTWASH analysis activity was performed. Specific attention was given to the numerical and experimental assessment of the ground vortex core position and velocity distribution.

1 Introduction
The activities described in this paper were under-taken as part of Brite Euram III project HELIFLOW BRPR-CT96-0206. The project objective (Ref. 1) was to improve experimental and theoretical tools for helicopter aeromechanic and aeroacoustic interactions. There were six experimental tasks in the project. Project members were Agusta, CIRA, DERA, DLR, Eurocopter, Eurocopter Deutschland, GKN-Westland, NLR, NTUA, ONERA, TUBS. DNW acted as subcontractor.

Task 3, led by Eurocopter Deutschland, addressed the low speed phenomena of sideward and quartering flight. During sideward flight in ground proximity, the helicopter main rotor induced ground vortex influences the main and tail rotor inflow conditions and thus its performance.

One of the Task 3 objectives was to establish an experimental database to be used for improving numerical prediction codes for analysing, among others aerodynamic phenomena in- and out-of-ground effect. Therefore wind tunnel tests were conducted with the DLR BO 105 scale 1:2.5 powered model in the Large Low-speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW). State of the art airflow test techniques were applied by DNW to measure the flow phenomena of the ground vortex. NLR contributed to the activities by performing ground vortex calculations and analysis.

2 Pre-test calculations
2.1 Use of OUTWASH code
NLR performed ground vortex pre-test calculations by applying its in-house developed MS-Windows based object oriented rotor outwash calculation tool OUTWASH, which includes a ground vortex calculation module. The OUTWASH code (Ref. 2 & 3) is being developed under a contract awarded by the Co-ordinator Spatial Planning and Environment Defence of the Ministry of Defence of the Netherlands.
The OUTWASH code consists of a semi-empirical method to calculate the horizontal outflow caused by the rotorwash (Ref. 4-7) and a finite element method to calculate developed vortices. The resulting horizontal flow velocities induced by the vortices are calculated using the Biot-Savard method on the calculated elements of the vortices. The calculation method used depends on the flight condition under consideration:

1. Hover and (very) slow forward flight or hover in moderate wind (recirculation regime).
2. Slow forward flight (about 9m/s < V_{fwd} < 13m/s) or hover in wind (ground vortex regime).
3. Forward flight at higher speeds (V_{fwd} > 18m/s) (trailing vortices regime).

Calculations can be performed for both single main rotor and tandem rotor helicopters (adaptation for tilt rotor aircraft is possible). Typical calculation time for a ground vortex flow field on a Pentium II PC is in the order of minutes, depending on the grid size.

To apply the code for the HELIFLOW Task 3 activities, OUTWASH has been extended with a 3D modelling of the displacement effect of the rotorwash and the presentation of vertical velocities induced by the ground vortex. To enable the direct comparison of experimental results with numerical predictions, the capability to calculate induced velocities in a randomly positioned vertical plane in the area of interest was added to OUTWASH, see figure 2.

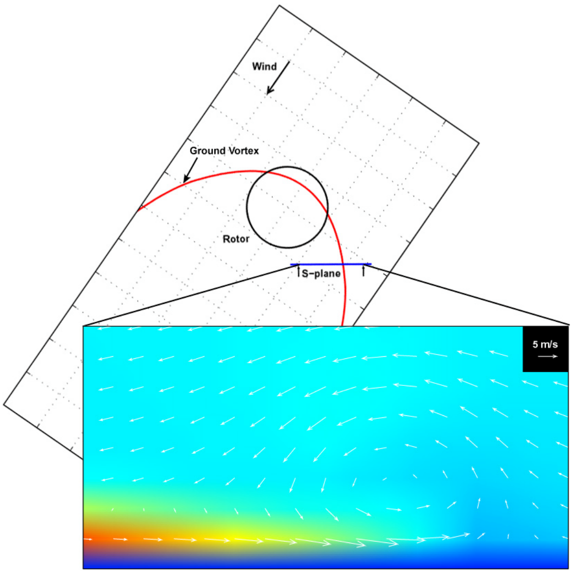

Figure 2 OUTWASH calculated ground vortex

Some additional data export features were also implemented to facilitate the production of the necessary figures. Reference 8 describes in more detail the code adaptations made.

2.2 Calculation results

Initial BO 105 main rotor ground vortex calculations have been performed for a large number of conditions (Ref. 8), including those defined in the preliminary wind tunnel test matrix. Calculations were performed for forward (equivalent to sideward) flight, and hover in wind case (for equal relative airspeeds), since, probably due to the differences in boundary layer profiles, the ground vortex develops in a different way.

Numerical results showed that for hover in wind, the ground vortex develops later (i.e. at higher wind speeds), is wider in size and exists over a larger range of relative airspeeds as compared to the forward flight case.
The significance of these differences led to the decision to apply Boundary Layer Control (BLC) by means of tangential air blowing during the wind tunnel campaign in the Large Low-speed Facility (LLF) of the German-Dutch Wind Tunnels (DNW). The BLC system blows a high-energy tangential air jet (2.4 kg/s) through a 1.0 mm slot (6 m width) in the wind tunnel floor upstream of the model into the wind tunnel boundary layer. In this way sideward flight conditions in-ground effect could be reproduced more realistically.
An OUTWASH parametric study was conducted to determine the sensitivity of the flow conditions to changes in tunnel speed and model height above ground. The results were used to refine the initial wind tunnel test matrix in terms of relevant wind tunnel test speeds and model height settings above ground for the in-ground effect test cases.
Furthermore, it allowed the experimental set-up for the flow measurements to be precised such that without changing the measurement equipment set-up, all ground vortex measurements could be conducted.

Figure 3 shows the vertical plane (indicated as laser light sheet) in which the ground vortex cross flow components were to be measured. The expected measurement results include the ground vortex core location and the velocity distribution in the measurement plane.

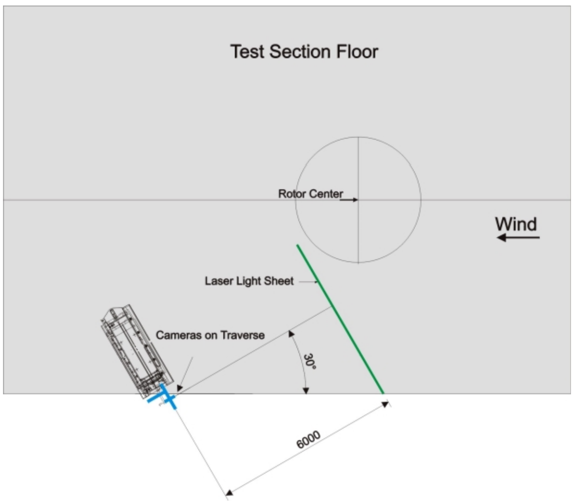

Figure 3 Location of measurement plane

3 Wind tunnel tests

3.1 Test set-up

A wind tunnel experiment was carried out in the DNW-LLF on a DLR BO 105 wind tunnel model. The model consisted of a powered main and 2-bladed tail rotor, drive & control systems, fuselage, 6-component rotor and fuselage balances and rotor sensors. The main rotor used is a 40%-geometrically and dynamically scaled model of the four-bladed, hingeless BO 105 rotor. The rotor system was mounted on DLR's Modular Wind tunnel Model (MWM) and driven by a 130 kW hydraulic motor. The model was mounted on a vertical sting support system, allowing adjustment of the rotor height above ground.

The model was operated at the full-scale nominal thrust level and tip Mach number. During the ground vortex measurement part of the test campaign, the main rotor was trimmed for zero blade flapping. The tail rotor was not operating during the ground vortex measurements.

In order to minimise the wind tunnel wall interference effects it was decided to use the 9.5 * 9.5 m test section of DNW-LLF in the open jet configuration (so-called ¾ open test section). To stabilise the flow, even at the relatively low wind speeds for the sideward flight tests (< 18 m/s), Seifert winglets were mounted at the wind tunnel nozzle to avoid low frequency pressure waves.

The ground vortex measurement arrangement in the three-quarter open test section of the DNW-LLF is presented in figure 4 (Ref. 9).

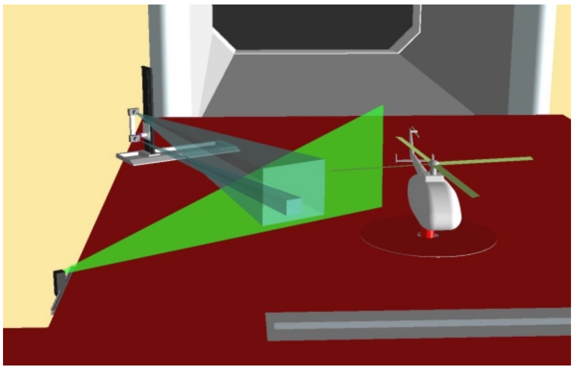

Figure 4 Test set-up in ¾ open test section

State of the art airflow test techniques were applied like Laser Light Sheet (LLS) and Particle Image Velocimetry (PIV) to measure the specific flow phenomena of the ground vortex on the advancing rotor side. The Nd-YAG-II laser heads (Quantel Brilliant B type) with a pulse energy of 350 mJ were located on the ground of the testing hall. The emitted beam was led to the light sheet generating optics by means of mirrors. This optical device was mounted at the edge of the test section floor. A mirror at the end of the optics directed the laser light sheet to the defined measuring location.

The flow was seeded in the settling chamber. The seeding rake (2.5 x 2.0 m) was connected to two seeding generators, equipped with Laskin nozzles to produce an aerosol of an adjustable particle size. The generated particles were droplets of about 1 µm in size; Di-2-Ethylhexyl-Sebacat (DEHS) was used as liquid. Due to the contraction of the flow in the nozzle the actual seeded circular area had a diameter of approximately 0.5 m.

Two PCO Sensicam double image cameras, which could be triggered externally, were used to record the PIV and LLS images (frequency of 3 images per second).
The size of the LLS image was 1.4 x 1.1 m. The PIV image size was 0.40 x 0.32 m. Both cameras were mounted on the same traversing system with the line of sight normal to the light sheet.

Both LLS and PIV images were taken with the camera in double frames / single exposure mode, which made it possible to determine the velocity distribution by means of image cross correlation. The resulting parameters for the vector grid are given in table 1.

Table 1 PIV and LLS vector grid parameters

Parameter		No. of pixels
PIV sampling window		32 by 32
Step size (PIV)		16 by 16
Grid (PIV):	X =	16.000 to 1264.000, 79 Nodes
	Y =	16.000 to 1008.000, 63 Nodes
LLS sampling window		64 by 64
Step size (LLS)		32 by 32
Grid (LLS):	X =	32.000 to 1248.000, 39 Nodes
	Y =	32.000 to 992.000, 31 Nodes

3.2 Test results

During wind tunnel testing, the LLS acquired speed vector map images were mainly used to localise the vortex core position. In addition, PIV images were taken in the vortex core area to precisely measure local flow conditions.
The vortex structure could be recognised by averaging the 36 instantaneous vector maps of each measurement sequence.

All PIV double-images were evaluated with a 32 pixel by 32-pixel sampling-window size, using 50% overlapping. The image size was 1280x1024 pixels. Achieved accuracy was 1.0 m/s. The corresponding LLS accuracy was 4.4 m/s.

Correlation of the LLS vector maps with the PIV vector maps resulted in the same vortex core position considering the spatial resolution of the LLS vector maps. This validates the LLS average vector maps. Since the LLS vector maps cover a larger area of the measurement plane, LLS vector maps are used in this report instead of PIV vector maps. Sample LLS and PIV average vector maps are shown in figure 5. The arrow colours and lengths indicate the magnitude of local flow velocities.

The LLS average vector maps have been used to determine the vortex core positions for a series of measurement runs in the LLS measurement plane.

In figure 6 and 7 respectively, the effect of rotor height above ground and tunnel speed on the vortex core positions is shown. On the vertical axis the vortex core height above ground is indicated, on the horizontal axis the distance from the origin of the measurement plane is given. The origin is defined at the lower left corner of the LLS measurement plane.

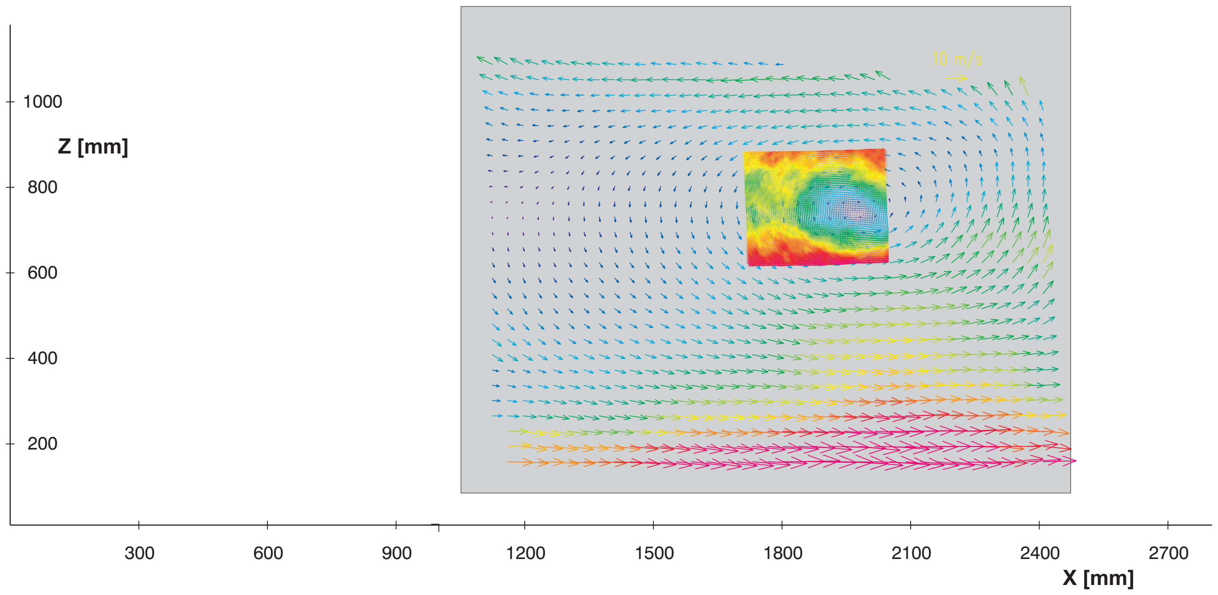

Figure 5 Ground vortex LLS average vector map

3.3 Results analysis

Table 2 lists the DNW test conditions where a clear vortex structure in the LLS measurement plane was identified and for which comparative OUTWASH calculations were performed.

Table 2 Test conditions with a clear vortex structure

DNW run	WT-speed [m/s]	Z_rotor [m]	Z_rotor / R [-]	Outwash
1002	10.9	1.48	0.74	101
1003	10.9	1.68	0.84	102
1004	10.8	1.88	0.94	103
1005	10.8	2.08	1.04	104
1105	10.7	2.28	1.14	105
1101	11.0	1.28	0.64	106
1010	11.0	1.48	0.74	107
1009	9.9	1.48	0.74	108
1007	7.6	1.48	0.74	109
1012	13.0	1.48	0.74	110

Changing the rotor height above ground from 0.64 R (run no. 1101) to 1.04 R (run no. 1005) causes the ground vortex core to move downward. Changing the rotor height further to 1.14 R (run no. 1105) does not move the vortex core more downward, but clearly moves the centre of the vortex core to the left. At lower rotor heights, apparently the presence of the fuselage prevents the ground vortex from moving downstream under the rotor. This could explain the limited horizontal movement (in the measurement plane) of the vortex core with changing rotor height. Further investigation into this effect is needed.

Reducing the tunnel speed at a constant rotor height above ground (0.74 R) from 13 m/sec (run no. 1012) to 9.9 m/sec (run no 1009) causes the vortex core to move along an almost straight line in an upward direction to the right. An interesting measurement point is the vortex core position at a speed of 7.6 m/s (run no. 1007). At this relatively low speed, the vortex core clearly moves downward. Further investigation into this phenomenon is also needed.

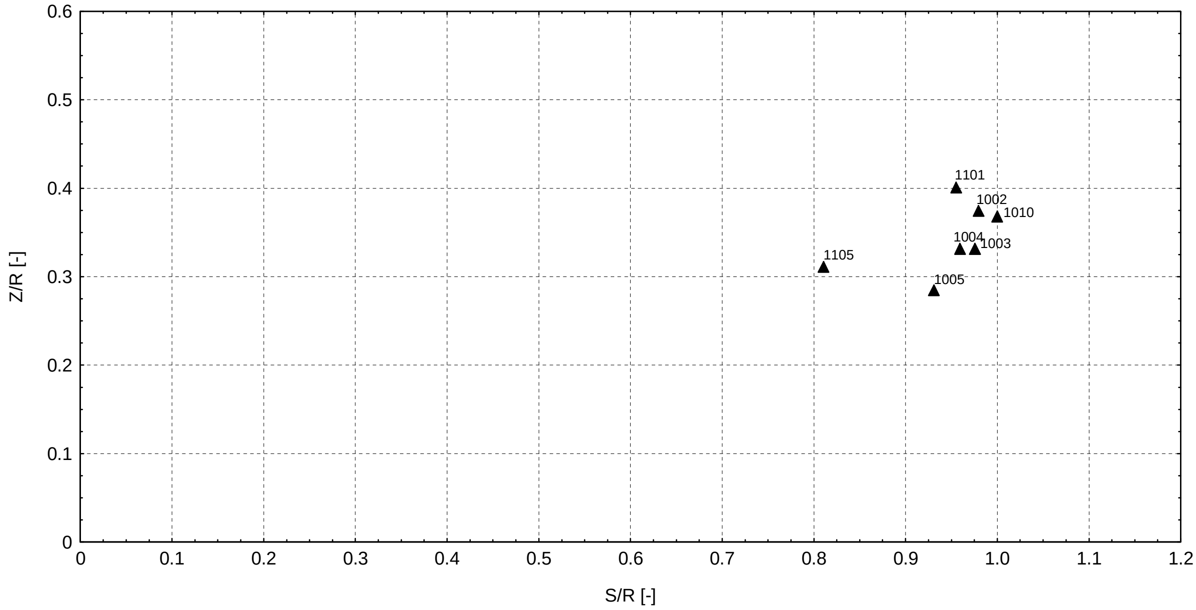

Figure 6 Measured ground vortex core positions in LLS-plane for varied rotor height

The ground vortex core position in the measurement plane is clearly much more sensitive to airspeed variations than to the rotor height variations under consideration.

The influence of the boundary layer thickness on the ground vortex structure was assessed by using a Boundary Layer Control (BLC) system. By means of the so-called tangential blowing it was possible to vary the boundary layer thickness between 20 and 80 mm (measured at the centre of the test section). For one test condition, the tangential blowing was switched off (boundary layer thickness of 80 mm). The effect of this difference in boundary layer thickness appeared to be small with respect to the vortex core position changes in the measurement plane due to variation of rotor height and tunnel speed variation.

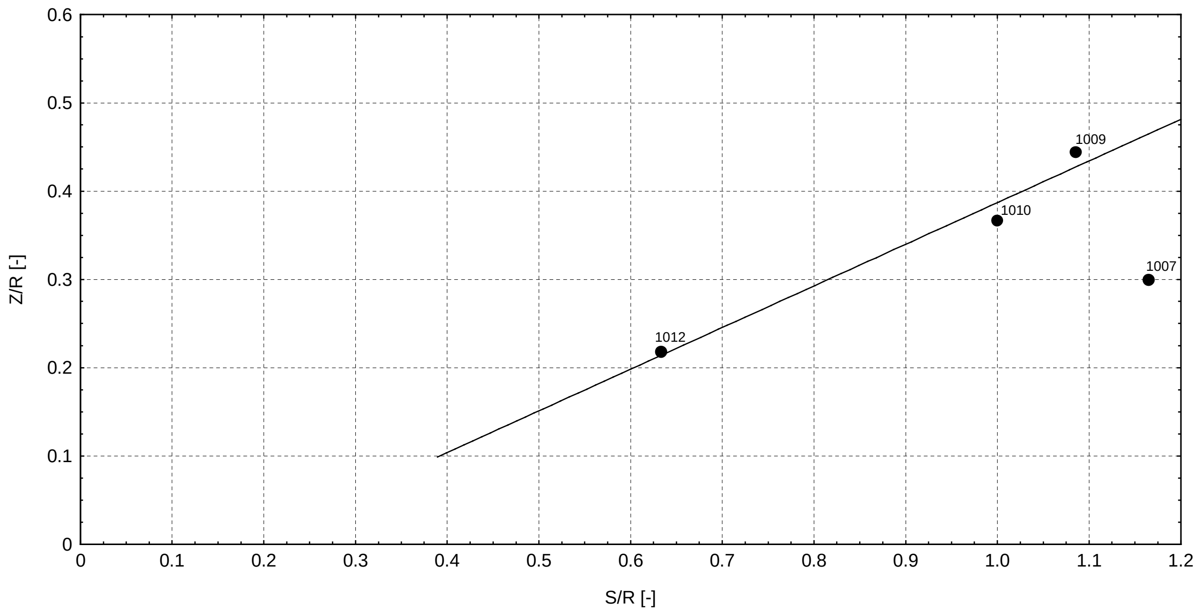

Figure 7 Measured ground vortex core positions in LLS-plane for varied air velocities

4 Comparison of predictions with experimental results

4.1 Post-test OUTWASH calculations

Initially the OUTWASH code has been applied for post-test calculations as used for the pre-test calculations. Only actual model configuration settings and wind tunnel conditions (tunnel speed, rotor thrust, rotor height above ground, boundary layer thickness) were changed. To include all measured conditions, the OUTWASH ground vortex occurrence range was extended slightly in height (from H/D < 0.5 to H/D < 0.6) and speed. Figure 8 shows the measured conditions where a clear vortex structure in the LLS measurement plane was identified and the (adapted) speed boundaries for the ground vortex flow regime as used in the code.

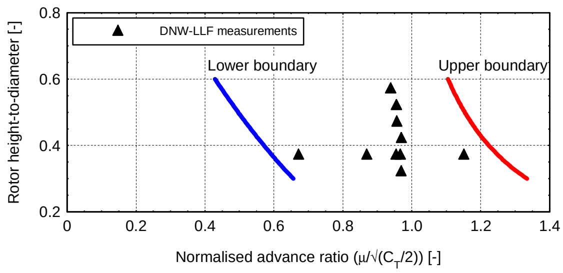

Figure 8 Boundaries for ground vortex flow regime

Figure 9 shows the comparative results between the measurements and the OUTWASH calculations. The calculations show a less wide vortex structure, resulting in vortex core positions closer to the origin of the measurement plane. Some conditions could not be reproduced, since the ground vortex tip already was “washed away” behind the rotor.

The differences between the calculation and experimental results are likely to be caused by the fact that the OUTWASH ground vortex module was tuned to isolated rotor measurement data; at the time of development the only reference data available. However, especially when operating close to the ground, a displacement effect of the fuselage can be expected. It forces the ground vortex to stay well in front and aside of the fuselage. This could explain the differences in position along the S-axis.

The differences in height (Z-axis) are likely caused by the effect of the rotorwash on the vortex tip (most forward part of the ground vortex). In the case of the OUTWASH calculations, without the presence of the fuselage, the ground vortex moves downstream under the rotor into the rotorwash. The rotorwash pushes the ground vortex tip downwards, resulting in a lower vortex core height as compared to the DNW-test measurements, where the ground vortex is not immersed in the rotorwash.

4.2 Matched OUTWASH calculations

Measurements were taken in only one vertical plane, which is not sufficient to reconstruct the whole ground vortex position and shape. So it was not possible to define one set of OUTWASH model parameters to match the BO 105 model ground vortex core positions for a wide range of conditions. However, with the OUTWASH model capabilities available, a parameter sensitivity study could be conducted. The results of this study are individually matched vortex core positions as shown in figure 10. It can be seen that the OUTWASH model contains sufficient tuning possibilities to adapt the ground

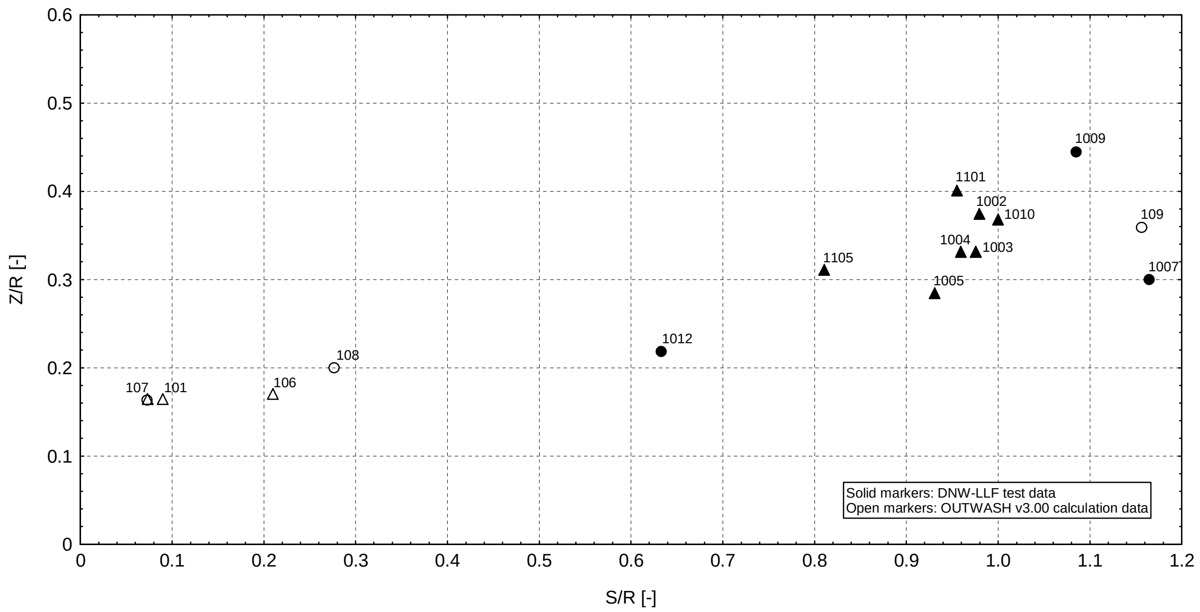

Figure 9 Comparison between OUTWASH (pre-test settings) and experimental results

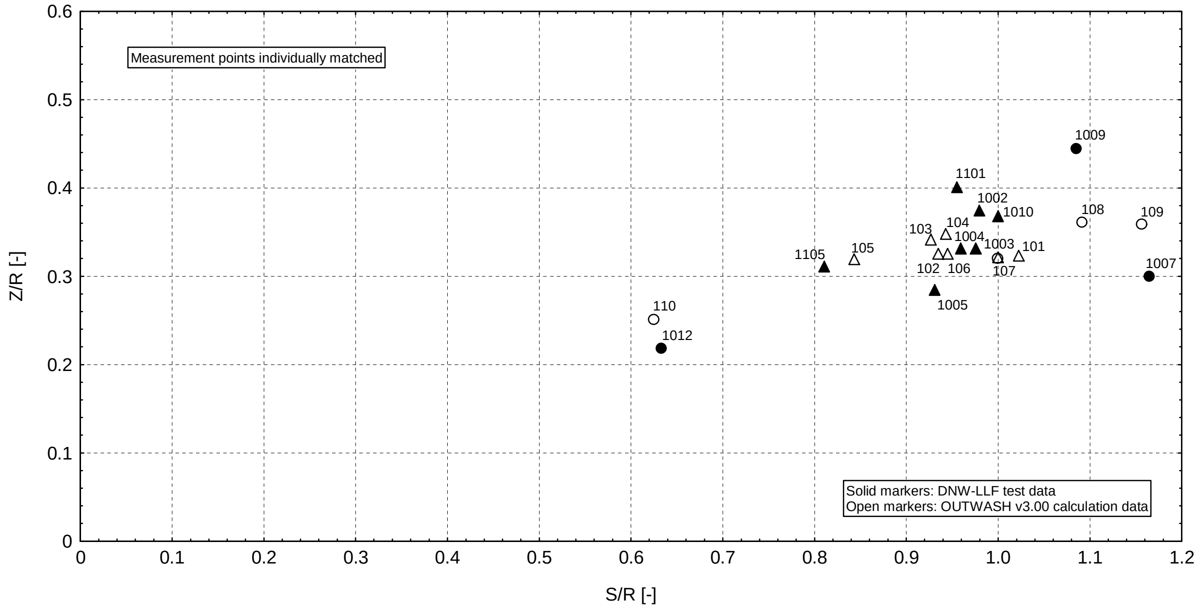

Figure 10 Comparison between OUTWASH (adapted settings) and experimental results

vortex position and shape to match with the measurement data.

It should be noted that the ground vortex shape is rather sensitive to the tunnel speed. A small change in the shape of the ground vortex frontal part leads to a relative large displacement of the vortex core position in the defined measurement / calculation plane. A change in tunnel speed therefore has a relatively large effect on the vortex core position in the measurement plane.

Besides the vortex position, also the calculated velocity distribution in the measurement plane has been compared with the LLS average vector maps as shown in figure 11.

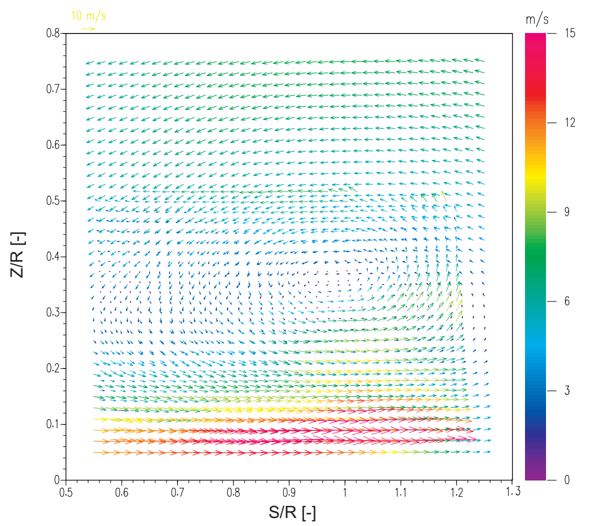

Figure 11 Comparative average vector map (run no. 1002 and OUTWASH condition no.101).

The calculated velocity distribution in the measurement plane shows good agreement with the LLS average vector maps.

The average velocity in a major part of the vortex is about 5 m/s, increasing to approximately 8 m/s in the outer vortex area. Close to the ground the highest velocities occur; values up to about 15 m/s have been calculated and values up to about 20 m/s have been measured.

5 Concluding remarks

This paper describes the HELIFLOW ground vortex experiment conducted in DNW's Large Low-speed Facility (LLF) and related numerical analyses.

The NLR in-house developed ground vortex calculation tool OUTWASH was used to refine the wind tunnel test matrix and to define the experimental set-up for the flow measurements to be executed. Wind tunnel tests were conducted with the DLR BO 105 powered wind tunnel model (scale 1:2.5). State of the art airflow test techniques were applied during testing to measure flow phenomena of the ground vortex.

Based on the test results obtained, an OUTWASH analysis activity was performed. The calculated local ground vortex velocity distribution showed good agreement with the measured average vector maps. Comparison of the calculated ground vortex core positions with experimental data was more difficult, due to the limited amount of test results available.

NLR's OUTWASH code clearly demonstrated the capability to predict the ground vortex shape and velocity distribution.

6 Acknowledgements

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7 References

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