Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2002-506

Aerodynamic investigations on a wing in ground effect

A summary of NLR activities in the Seabus-Hydaer programme

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Summary

This report highlights the activities of NLR in the Seabus-Hydaer programme, performed under a contract awarded by the European Commission. This programme was to evaluate the feasibility of a large wing-in-ground-effect vehicle to be used for fast transport over sea, cruising at a speed of at least 100 kts and carrying 800 passengers plus 100 cars over a distance of 850 kms. The project was led by Intermarine, a shipbuilding yard in Italy.

The concept features hydrodynamic control by hydrofoils rather than aerodynamic control. These control hydrofoils are connected to the wing by vertical water surface piercing struts. Separate V-shaped hydrofoils are used to generate hydrodynamic lift forces to assist in take-off to get the hull out of the water before the air speed is reached for the wing to fully carry the weight of the vehicle.

As one of the eleven partners in the project, NLR was responsible for the aerodynamic analysis and the verification by wind tunnel tests. NLR also participated in the overall design activities as member of the Design Review Board that was formed during the project.

The report describes the aerodynamic evolution starting with the initial design provided by Intermarine, some results of the aerodynamic calculations, the wind tunnel test and the main results obtained for take-off and cruise conditions.

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List of symbols

C_D	vehicle aerodynamic drag coefficient
C_L	wing lift coefficient
C_M	aerodynamic moment coefficient
h	vertical distance between sea level and wing bottom at 25 % chord
L/D	aerodynamic lift - to - drag ratio
mac	mean aerodynamic chord
SPW	surface piercing wing
α	angle of attack (zero with (flat) wing bottom horizontal)
δ_F	flap angle

1 Introduction

The Seabus-Hydaer programme, performed under a contract awarded by the European Commission was to evaluate the feasibility of a large wing-in-ground-effect vehicle to be used for fast transport over sea, cruising at a speed of at least 100 kts and carrying 800 passengers plus 100 cars over a distance of 850 kms.

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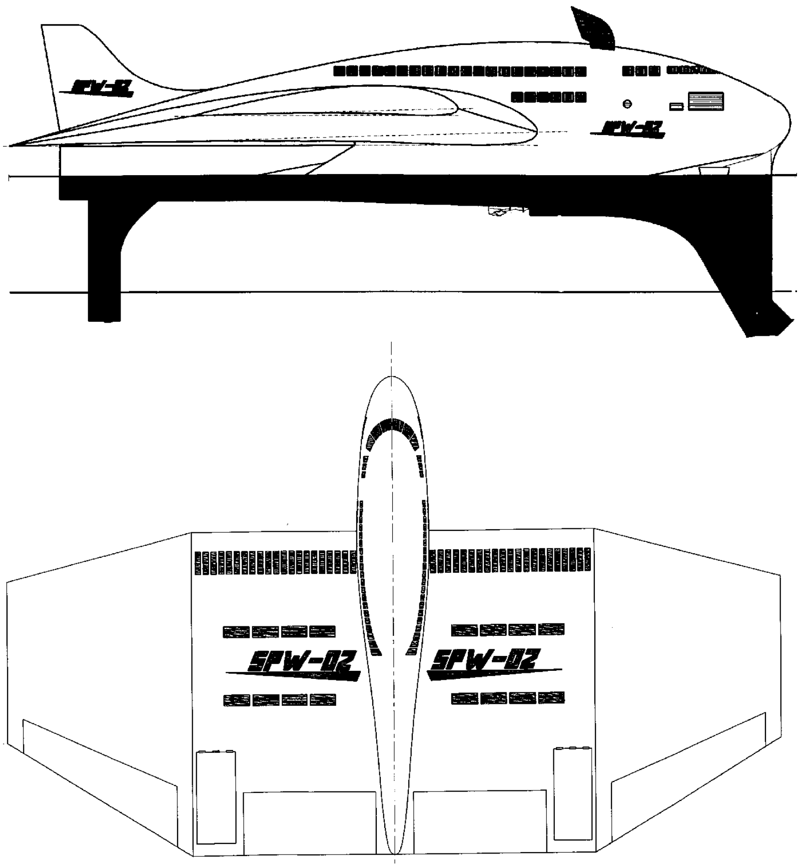

Fig. 1 Original SPW-02 design

2 General description of the NLR activities

Starting with the initial design SPW-02 provided by Intermarine (Fig. 1), preliminary performance calculations were made. The required aerodynamic data were obtained from computational aerodynamic methods at NLR. The hydrodynamic characteristics were obtained from the partners. The results were reported in reference 1.

It turned out that the lift capability of the selected Göttingen 1020 airfoil of 11.2 % percent thickness had to be improved by choosing a thicker airfoil. NLR designed a 13.7 % thick flat bottom airfoil that would meet the cruise requirement of being able to lift 500 tons at 120 kts at zero angle of attack (wing bottom horizontal) and zero flap angle. Although the wing showed promising cruise performance capabilities, it turned out that at 120 kts cruise speed the hydrodynamic drag would comprise 2/3 of the total drag. Minimum airborne speed was predicted at 70 kts.

As a second step, the design was modified by Intermarine leading to a smaller wing span of 100 metres and a reduction of the wing area by 25 percent while maintaining the take-off weight at 500 tons. At the same time the cruise altitude was increased from 9 to 11.5 meters or from 18 percent to 30 percent of the mean wing chord, thus reducing the favourable ground effect on the aerodynamic performance. An airfoil with a thickness of 24.3 percent was designed by NLR to meet the cruise requirements (500 tons lift force at 120 kts and zero angle of attack). Figure 2 shows the three airfoils together and conclusions were presented at the Mid Term Assessment Meeting, December 1999 (month 17 of the project). The minimum airborne speed with deflected flaps was predicted at 77 kts.

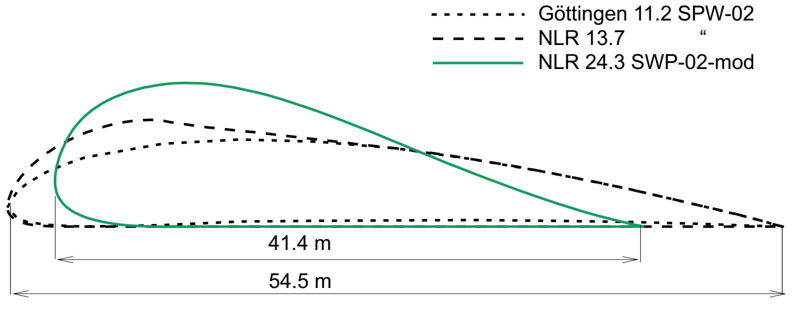

Fig. 2 SPW-02 and SPW-02-mod airfoils designed by NLR

To speed up convergence of the design it was decided at the Mid Term Assessment Meeting to establish a Design Review Board in which NLR agreed to participate for the aerodynamic design aspects. For reasons of cost, use had to be made of engineering methods taking into account the results of the earlier and a limited number of new CFD calculations.

In November 2000 the design could be declared frozen. The following improvements and modifications to the aerodynamic design were adopted, see figure 3:

- The water jet propulsion system was replaced by air propulsion leading to less hydrodynamic drag and a better propulsive efficiency (less fuel burn).
- The cruise angle of attack of the flat bottom of the wing airfoil was increased from 0 to 5 degrees to improve height stability (lift should decrease when flying higher). This allowed at the same time to reduce the airfoil thickness from 24.3 to 18 percent. A higher angle of incidence of 6 degrees was selected for take-off, requiring a different vertical position of the front and rear take-off foils (not shown in Fig. 3).

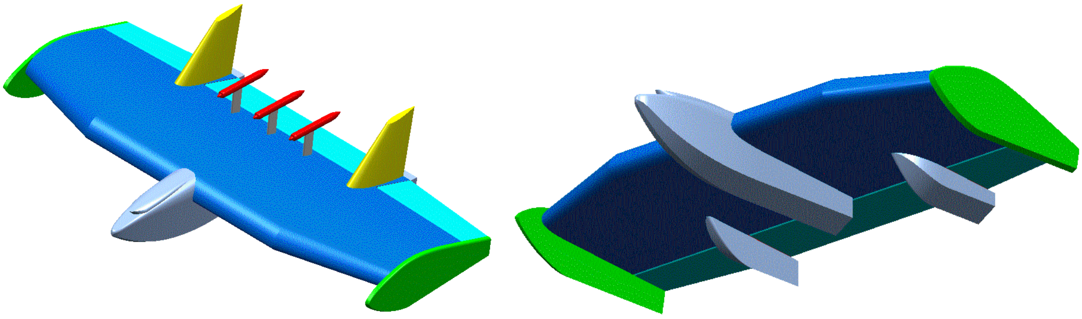

Fig. 3   Seabus frozen aerodynamic design configuration

- The central fin was replaced by a twin fin configuration, the central flap became uninterrupted by reducing the length of the central hull and the flap hinge lines at the outer wing sections were aligned with the hinge line on the central wing section. Slotted Fowler flaps at the wing trailing edge were replaced by plain flaps to reduce vulnerability for water spray effects (corrosion).
- To improve the aerodynamic performance (more lift, less induced drag), end plates were added to the wing tips.

After the design freeze the aerodynamic characteristics were re-evaluated including stability and control considerations. This resulted in a report on the aerodynamic performance of the frozen design to be expected on the basis of engineering methods and earlier and additional CFD calculations (Refs. 2 – 4) to be used by Gamesa and Alenia Marconi for further analysis and preliminary input for the dynamic simulation model. These data were to be updated by the results from the wind tunnel model tests.

Figure 4 shows an example of the pressure distribution on the clean wing (without hulls, end plates and fins) according to the frozen design as calculated by CFD without viscous effects (Ref. 2). Other CFD results are found in Ref. 3. Integration of the pressure forces leads to a lift coefficient $C_L = 0.86$ at 5° angle of attack, zero flap deflection and a flight altitude of 12 metres. Wind tunnel measurements on the same clean wing showed $C_L = 0.74$.

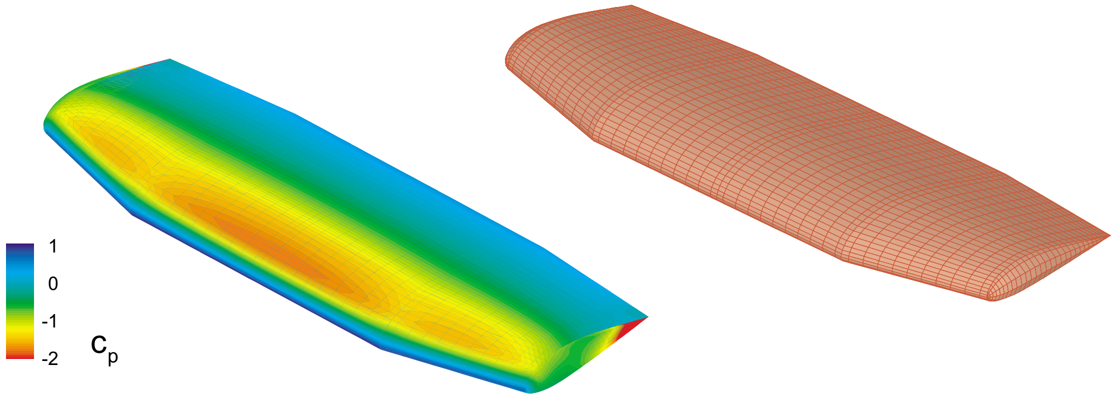

Fig. 4 Computational grid and pressure distribution without boundary layer effects on clean wing at cruise condition ($h = 12$ m, $\alpha = 5°$, $\delta_F = 0$)

After the various decision points concerning model specification (Ref. 5), wind tunnel test plan (Ref. 6), model geometry, model drawings, the models were completed and tested in April 2001.

Figure 5 shows the models mounted in the wind tunnel. The lower model is a dummy that simulates the ground effect on the forces and pressures that are measured on the upper model.

A meticulous correction procedure appeared necessary for the interference of the support strut on the pressures and forces on the top of the wing centre section. This correction was developed using earlier CFD results in comparison to the clean wing test data and additional pressure measurements in the interference area, see figure 6 (showing add-on pressure taps and tufts for flow visualisation).

At mid July 2001 the final test results were sent to Gamesa and Alenia in the form of a data base as agreed (Ref. 7), followed by an analysis report in October 2001 (Ref. 8).

Fig. 5 Seabus wind tunnel models with 30° flap deflection

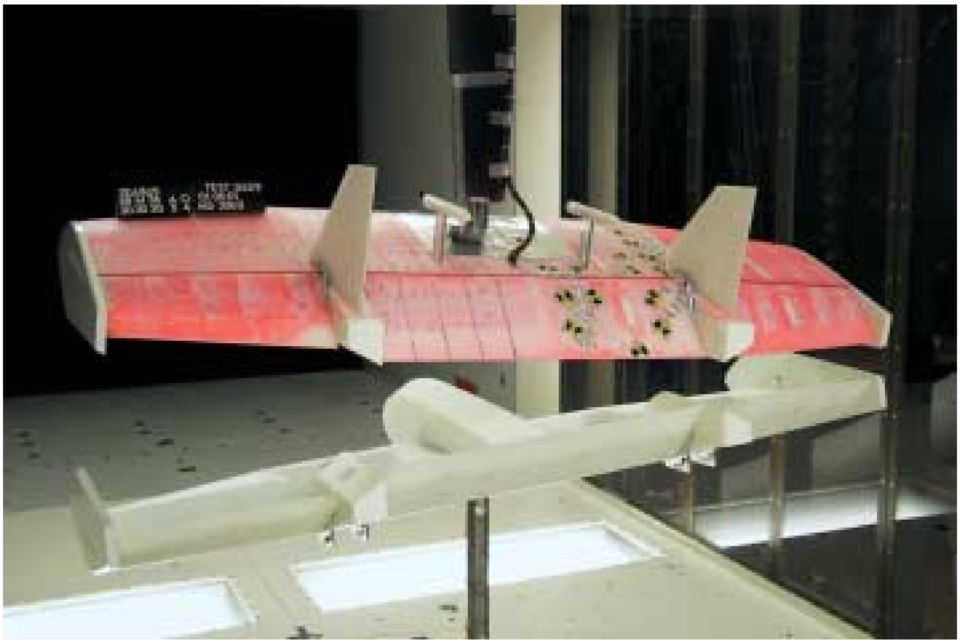

Fig. 6 Seabus wind tunnel model with additional instrumentation

3 Main aerodynamic performance data

Some main results concerning the cruise and take-off condition are given below and compared to the engineering predictions

Cruise performance $\alpha = 5°$, h = 12 m, zero flap deflection			
		predicted	W/T test
Angle of attack	α	5°	5°
Flight altitude	h	12.0	12.0
Lift coefficient	C_L	0.82	0.79
Drag coefficient	C_D	0.052	0.067
Lift to drag ratio	L/D	15.8	11.8
Moment coefficient	C_M	-0.101	-0.085
Centre of lift	X_{cp} (% mac)	12.3	10.7

The measured cruise lift coefficient is close to the predicted value. At 98.7 kts (50.8 m/s) a wing lift of 500 tons would be generated at $C_L = 0.79$.

The aerodynamic drag would amount 42.4 tons. To overcome this drag a power is needed of 21.1 MW. (Power in Watt = drag force in Newtons × flight speed in m/s)

The centre of lift is located at 10.7 percent of the mean aerodynamic chord behind the vehicle reference point (at 25 % chord behind the centre wing leading edge) and 1.6 percent mac ahead of the predicted location.

Take-off performance $\alpha = 6°$, $h \approx 10$ m, 30° degrees flap deflection			
		predicted	W/T test
Angle of attack	α	6°	6°
Flight altitude	h	10	10
Lift coefficient	C_L	1.72	1.74
Drag coefficient	C_D	0.198	0.188
Lift to drag ratio	L/D	8.7	9.2
Moment coefficient	C_M	-0.243	-0.245
Centre of lift	X_{cp} (% mac)	15.5	16.6

The angle of attack $\alpha = 6°$ at lift-off results from the difference of the mounting height between the front and rear take-off hydrofoils.

It is concluded that for take-off a lift coefficient $C_L = 1.7$ is achievable as assumed in the engineering prediction. For a wing lift of 500 tons the take-off speed would be 67.4 kts = 34.7 m/s without head wind. The aerodynamic drag would amount 57.5 tons requiring 19.6 MW propulsive power. The centre of lift is close to the predicted value and is 16.6 – 10.7 = 5.9 percent mac behind the location at cruise.

4 Technical progress made

4.1 Definition of hydro/aerodynamic interactions in stability and control

During the project it became clear that problems associated with vehicle stability and control and the interaction between aerodynamic and hydrodynamic control surfaces had been highly underestimated. NLR has strongly contributed to obtain the required understanding and its implementation in the design of the vehicle.

4.2 Identification and quantification of wind effects

Also, the effect of wind on the take-off and cruise performance was identified as a new issue. At cross wind directional stability provided by the hydrofoil struts will cause zero cross flow under water but the aerodynamic part will not be aligned with the air speed leading to increased drag and to performance degradation. The wind tunnel tests showed that a 10° cross wind will increase the aerodynamic drag at cruise conditions by 30 %. This is of the order of 15 % of the total drag (aerodynamic plus hydrodynamic drag). A compromise is required between yaw angles in air and water to minimise drag.

4.3 Effect of water waves on flight altitude constraints

The effect of water waves on the required accuracy of altitude and bank angle control was investigated as part of the wind tunnel test program definition. In the airborne mode the altitude must be sufficiently large to avoid hitting wave crests by the take-off foils in the airborne mode on one hand (h_{min}) and sufficiently small to keep the control hydrofoils more than 2 meters below the wave troughs (h_{max}). At zero wave height and $\alpha = 5°$ the altitude h must be kept within $10.65 < h < 14.22$ m where h is the altitude of the vehicle reference point above the average sea level.

For a wave height of 1.7 m (trough to crest) the boundary is reduced to $11.50 < h < 13.37$ meters. When, in addition, the wing has a bank angle of 2° the flight altitude (measured at the plane of symmetry) must be kept within $11.50 < h < 12.53$ m. This requires a flight control accuracy that maintains h at 12 m with an accuracy of ± 0.5 m while the bank angle is kept smaller than 2°.

4.4 Flap retraction scheme during acceleration

In figure 7 the flap angle variations are shown that are required to keep the wing lift constant at 500 tons at different air speeds at an angle of attack of 5 degrees, based on the wind tunnel test results. During the acceleration phase just after lift-off the flaps should be retracted at a rate of 2 degrees per knot increase of the air velocity to keep the wing lift force constant.

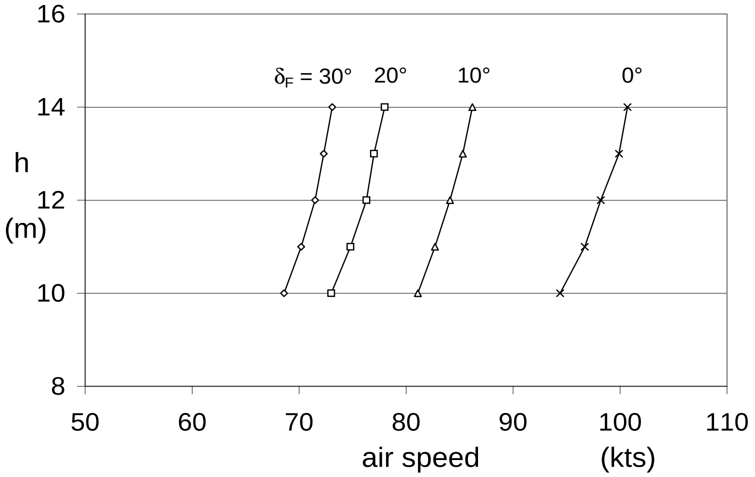

Fig. 7 Flap angle variations required to keep the wing lift force constant at 500 tons

Due to the low wing loading (20 % of a Boeing 747 aircraft) required for a low take-off speed, the vehicle is rather sensitive to variations of the wind velocity and a gust of 2 kts requires a correction of 4 degrees flap deflection to avoid a vertical acceleration just after the lift-off.

4.5 Mirror model technique for wind tunnel simulation of ground effect

During preliminary research at NLR outside the present scope of work it was discovered that a ground board with blowing of the wall boundary layer did not provide a realistic simulation of the ground effect and that a dummy model in mirror image position was required. This was unexpected since boundary layer blowing is a well established technique for automobile testing.

4.6 Development of low-cost model design and manufacturing techniques

The conclusion that two models were needed in stead of one combined with a cost reduction required by the contractor stimulated inventiveness for alternative model design and manufacturing methods. This included a mixed construction of wooden framework, computer controlled manufacturing of contoured model parts by Fused Deposition Manufacturing in ABS (a nylon like material) and metal bracket parts for manual adjustment in fixed steps of the various angles (angle of attack, flap angles, roll angle). Figure 8 shows all model components before assembly.

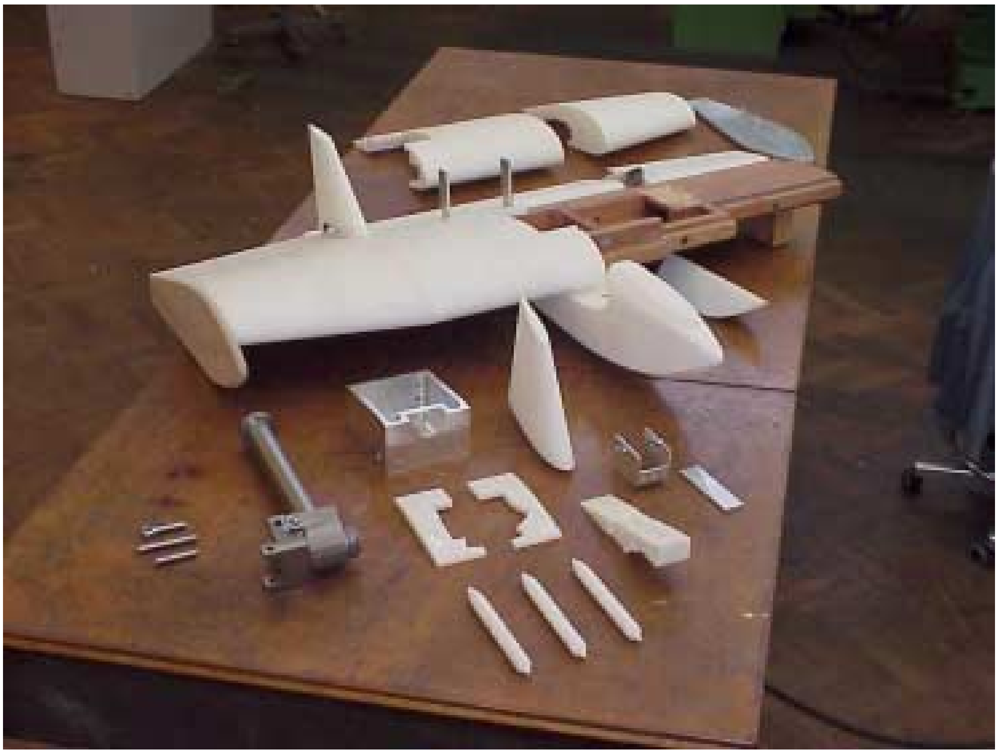

Fig. 8 Seabus wind tunnel model components before assembly

4.7 Development of wind tunnel strut interference correction procedure

The integration of CFD calculations and experiments proved to be vital for development of a correction procedure for the strut interference. This interference was much larger than on conventional aircraft models but was difficult to avoid in this mirror model test set up.

5 Conclusions

Within the Seabus consortium considerable knowledge has been obtained on the complexity of a concept that should combine the advantages of improved aerodynamic efficiency obtained from a wing in ground effect with the advantages of water jet propulsion and small hydrofoils for stability and control at speeds of 100 knots and higher.

It was demonstrated from wind tunnel experiments that the Seabus wing with an aspect ratio of 2.55 with hulls and end plates at the tips can achieve a lift to drag ratio of 11.8 at cruise condition at a height of 12 m above the sea level. This is slightly lower than for civil transport aircraft.

The hydrodynamic forces on the vertical struts will tend to keep the vehicle aligned with the ground speed. This leads to 30 percent increase of the aerodynamic drag in a 10 degrees cross wind resulting in a lift to drag ratio L/D = 9.

To keep the control foils sufficiently deep under water and to avoid that the take-off foils hit the wave crests very accurate flight control is required keeping the altitude within ± 0.5 m and the bank angle smaller than 2° when the wave height is 1.7 m (trough to crest). Lower wave heights exist in the Mediterranean Sea area during 75 percent of the time.

The study has demonstrated that the combination of aerodynamic lift and hydrodynamic controls has a negative effect on the cruise performance of a high-speed wing-in ground-effect transport vehicle and sets high requirements to controllability.

NLR has extended considerably its knowledge on the aerodynamics of wings-in-ground-effect and has demonstrated successfully the application of Computational Fluid Dynamics, engineering prediction methods and wind tunnel test techniques to support the Seabus-Hydaer programme.

A unique combination of interdisciplinary expertise on aerodynamics, hydrodynamics, propulsion, structural design and operational aspects has been acquired in the Seabus consortium that is now available for the technical evaluation of other concepts of high speed sea transport systems. NLR contributes to this expertise in the field of aerodynamics, stability and control, including analysis and design activities.

6 Acknowledgements

NLR wants to express their acknowledgements to all partners of the Seabus consortium but in particular to the initiating partners Intermarine and Alenia Marconi who continued to support the Seabus programme in its adapted form despite some divergence between their company interests and the expectations for the overall project.

7 References

1. Beek, C.M. van; Oskam, B.; Fantacci, G.; *Progress report on the aerodynamic analysis of a surface piercing hydrofoil-controlled wing-in-ground effect Seabus configuration*, NLR-TP-98510.

2. Beek, C.M. van; *CFD computations on the wing of the Seabus configuration*, NLR-TR-2001-358.
3. Sandkuijl, P.; Beek, C.M. van; *Aerodynamic performance data of a large size, low aspect ratio wing operating in ground effect*, NLR-TR-2001-550.
4. Wolf, W.B. de; *Engineering prediction of Seabus aerodynamic performance*, NLR-TR-2001-030.
5. Wolf, W.B. de; *Specification for a Seabus wind tunnel model*, NLR-CR-2001-255.
6. Wolf, W.B. de; *Wind tunnel test program for a Seabus model in ground effect*, NLR-CR-2001-254.
7. Souren, R.M.; *Test Data Report Seabus-Hydaer, Test Number 0629*, DNW TR 01.11, Sept. 2001.
8. Wolf, W.B. de and Ganzevles, F.L.A.; *Wind tunnel test results on a Seabus model in ground effect*, NLR-CR-2001-471.