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GROUND EFFECT INFLUENCE ON THE AERODYNAMIC CHARACTERISTICS OF ULTRALIGHT HIGH-WING AIRCRAFT – WIND TUNNEL TESTS

Robert Placek, Paweł Ruchała, Wit Stryczniewicz

Institute of Aviation, Department of Aerodynamics,
Krakowska Av. 110/114, 02-256 Warszawa, Poland
tel.: +48 22 846 00 11 ext. 360, 312
e-mail: robert.placek@ilot.edu.pl, pawel.ruchala@ilot.edu.pl
wit.stryczniewicz@ilot.edu.pl

Abstract

The ground proximity may significantly improve the performance of the aircraft, but in some conditions, it affects its stability. The gain of lift which and reduction of drag during low altitude flight is known as the wing in ground effect (WIG effect). It may concern aircrafts or WIG-crafts (ground effect vehicles). In the article experimental results of the wind tunnel test of an aircraft in ground effect has been presented. The main aim of the test was to investigate the ground effect influence on aerodynamic characteristic of the of the ultralight high-wing aircraft model during early take off, taxiing or final landing stage. Investigation was carried out in the 1.5 m diameter low speed T-1 wind tunnel in the Institute of Aviation in Warsaw. The velocity was 32 m/s and Reynolds number related to the aerodynamic chord was equal about $0.37 \cdot 10^6$. *Tests were performed for chosen angles of attack in range 0-10°. During investigation, the strain gauge balance measurements and Particle Image Velocimetry (PIV) flow visualization technique were applied. Tested model position was relatively close to the ground. It was found, that the ground proximity has significant influence on the pitching moment. The normal force was increased and the axial force is decreased due to the WIG effect, which is compatible with the theory. It has significant meaning for control aircraft issue and safety.*

Keywords: *ground effect, aerodynamic characteristics, high-wing ultralight aircraft, wind tunnel research*

1. Introduction

It is well known that in close proximity to the ground the aerodynamic characteristics of a wing change considerably, something that has come to be known as wing in ground (WIG) effect [3]. In general, the performance of wing in the proximity of ground is increased. This effect may be utilized in ground effect vehicles, known also as WIG crafts. These vehicles are becoming promising transportation over the last decade [5], however first investigations concerning an influence of ground on the streamlines around an airfoil have been conducted in 1920s ([15, 16]), and the idea of using ground effect to improve lift was introduced as early as 1930 [12]. A history of WIG crafts development has been presented i.e. in [17] and their performance and design conception has been discussed in [14] and [7]. The WIG effect has been investigated experimentally, both in the past [18] and in recent years ([4, 8]).

WIG crafts may be breakdown into three types [5, 11]: type A: No out of ground effect capability, in which the craft is certified only in ground effect; type B: Flight capability up to 150 meters or 500 feet, in which certified to temporarily increase its altitude to a limited height stated, outside the influence of the ground effect, type C: Full flight capability (aircraft), in which certified to operate exceeding 150 meter above surface.

It must be underlined that the WIG effect may concern classic aircrafts (WIG crafts type C), during taxiing or low-altitude flight. The wing-in-ground effect, according to [1], is a combination of two phenomena. First phenomenon is a reduction of the induced drag. The wingtip vortices in the proximity of ground are not fully developed. Moreover, the vortices are pushed outwards by the ground, which increases effective aspect ratio of the wing. This effect is related with the height-to-span ratio, so is called a span dominated ground effect (Fig. 1).

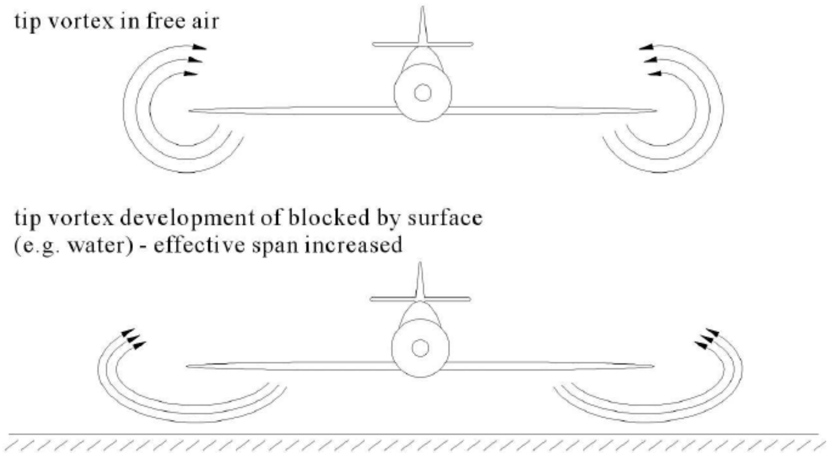

Fig. 1. Explanation of the span-dominated ground effect [1]

Second phenomenon involved in the WIG effect is raise of lift, related with an increment of static pressure of the airstream caused by the proximity of ground (air cushion). This phenomenon is related with height-to-chord ratio and is called a chord dominated ground effect. Abramowski in [1] claims that this effect may be positive under following conditions: the pressing side of the airfoil should be as flat as possible and the angle of attack should be positive. Otherwise, when the bottom of the foil is convex and the angle of incidence is very low or negative, between the foil and the ground a Venturi nozzle is created where high-speed low-pressure air suck the airfoil down. The lift enhancement, according to numerical experiments performed by Abramowski, is given by equation:

$$C_{L\,ground} = C_L \cdot \left(\frac{H}{c}\right)^{-0.11}, \tag{1}$$

where:
$C_{L\,ground}$ – lift coefficient in proximity of the ground,
C_L – lift coefficient without the ground effect
H – height of flight (above the ground),
c – wing chord.

The WIG effect may also have significant contribution in the stability of the craft. In fact, as it is stated in [6], stability and control problems faced by the WIG in earlier development are still unresolved. It was observed that variations of the longitudinal stability caused by the ground proximity are responsible for substantial changes in the landing trajectories, especially during the flare-out manoeuvres [9, 19]. In [9] de Divitiis found that during horizontal flight with $\varphi = \beta = 0$, the ground plane imposes a boundary condition on the aerodynamic field that symmetrically reduces the downward flow about the aircraft. Moreover, this phenomenon may be gained because of relation of and lift generated by the tail and its distance from the ground. Therefore, says de Divitiis, the aerodynamic coefficients, which are a function of both height and aerodynamic angles, also vary with the Euler angles. This effect, which modifies performance and flying qualities, is observed by pilots when an aircraft is close to the ground. For example, during flight tests on W.I.G. vehicles [13], horizontal banked turns were carried out to demonstrate that the sideslip, rudder and ailerons angles are quite different from those without ground effect. While these angles are quite small for steady banked turns out of ground effect, for a W.I.G. craft they are quite large.

2. Test object

The geometry of the test object was based on the MP-02 ultralight aircraft, which is a high-wing aircraft with the T tail. The scale of the model was about 1:9 and its dimensions were as follow: mean chord 0.12 m, span 1.08 m, wing area 0.129 m^2. Model was adjusted in order to perform balance tests in the low speed wind tunnel. For this purpose, in the fuselage of the model the special mounting of strain-gauge balance was designed. The picture of the tested model in the wind tunnel test section is presented in Fig. 2.

Fig. 2. Model of the ultralight aircraft mounted in the test section of the T-1 low speed wind tunnel

3. Approach and tests

The WIG tests were performed in low speed, close circuit T-1 wind tunnel with 1.5-meter diameter open test section. The tests were carried on at flow velocity equal 32 m/s. Test object – high-wing aircraft model was tested with and without ground presence. During investigation, as the ground imitation, the flat plate was mounted under the model. Because of the unwanted boundary layer thickening along the flat plate during wind tunnel tests, which does not take place in real situation during low flight at the ground, the ground imitation was mounted at specified, constant inclination angle. In order to estimate its value, before the main test, the boundary layer thickness and its change along the plate measurement were performed with use of Constant Temperature Anemometry (CTA) and PIV techniques. From given data, the mean angle of the boundary layer thickening under predicted model position, was obtained.

The tests with the ground imitation were performed in the two manners. At first, the bottom of the model main landing gear, independently of model pitch angle, was on the border of the boundary layer. For this case according to the angle of attack increment, the *H/c* ratio changed in range 1.65-1.83, depending on the pitch angle. Secondly, the ground imitation was lowered and *H/c* ratio assumed values as 1.98-2.15. The H/c distance was measured from the leading edge of the mean wing chord to the boundary layer.

In order to change position, model was supported, by mounted inside the 6-component aerodynamic balance on the pitching, vertical sting. During tests, model pitch angle was changed in range: α_p ⟨0-10º⟩. The model point of reference was positioned approximately in 27% of the mean wing chord on its x-axis.

As additional tests, the PIV measurements were performed with application of the methodology described in [21] and [22]. The area of interest was space between wing and tail. Velocity measurement has been performed in vertical plane, distanced from the symmetry plane of 120 mm (85% of span of horizontal stabiliser). The flow visualization was performed at free stream velocity 26 m/s.

4. Data reduction

The aerodynamic loads acting on the model were measured and recorded by use of the measurement and control system of the wind tunnel T-1 [19]. Data were initially written as the values of voltage, indicated by balance. Next, the reduction of measurement data was performed by authors' computer program "Unsteady T 1.vi". The following operations were initialized:

1. Transforming data from voltages values into loads in balance coordinate system;
2. Transforming balance loads into model coordinate system (see Fig. 3);
3. Data filtering (with the low-pass zero-phase digital filter) and time synchronisation;
4. Transforming loads on to aerodynamic coefficients as below:

$$Ct = \frac{T}{q \cdot S}, \quad Cn = \frac{N}{q \cdot S}, \quad Cm_{pitch} = \frac{M_{pitch}}{q \cdot S \cdot c}, \tag{2}$$

where:

T, N – aerodynamic forces referred to model coordinate system,
M_{pitch} – aerodynamic moments referred to model coordinate system,
c – mean chord,
b – wing span,
S – wing area.

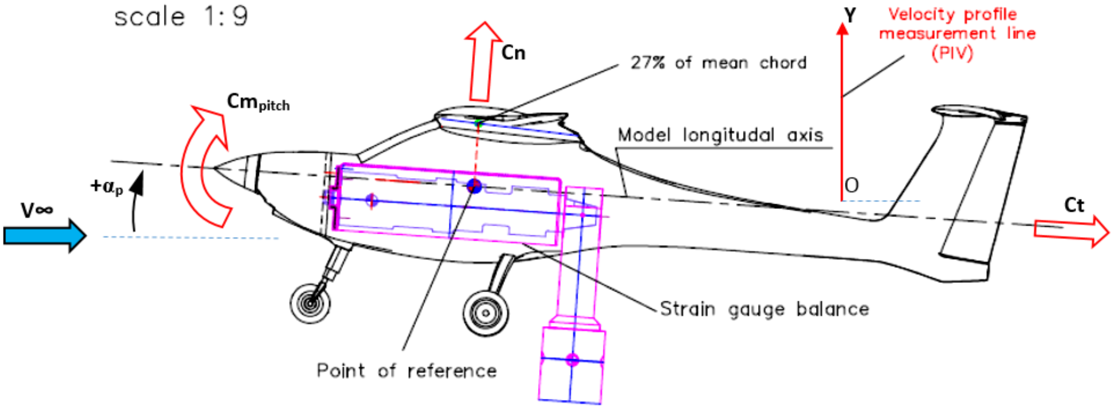

Fig. 3. The model coordinate system

5. Results

The force and moment coefficients of the high-wing ultra-light aircraft model with and without ground effect, given in the model coordinate system, are presented in Fig. 4-6.

The comparison of the two test cases with the ground presence revealed that the most significant change concern the pitching moment coefficient and is equal up to 6% of its variation range. Normal force coefficient Cn and tangent force coefficient Ct changes up to 2% and 4% of their variation range, respectively.

The more significant changes are seen, when comparing test cases with and without ground presence. The higher model pitch angle, the higher differences in coefficients value is seen. The most significant change appears for the pitching moment coefficient, from 11% to 30% of the variation range. Greater values of the pitching moment coefficient are achieved without presence of ground.

The WIG effect caused also a decrement of tangent force coefficient, from 5% (at pitch angle of 0) to 23% (at pitch angle of 8°) of the variation range. Moreover, the normal force coefficient due to ground proximity increases from 5% to 10% of variation range. Its highest increment appears for moderate values of pitch angle.

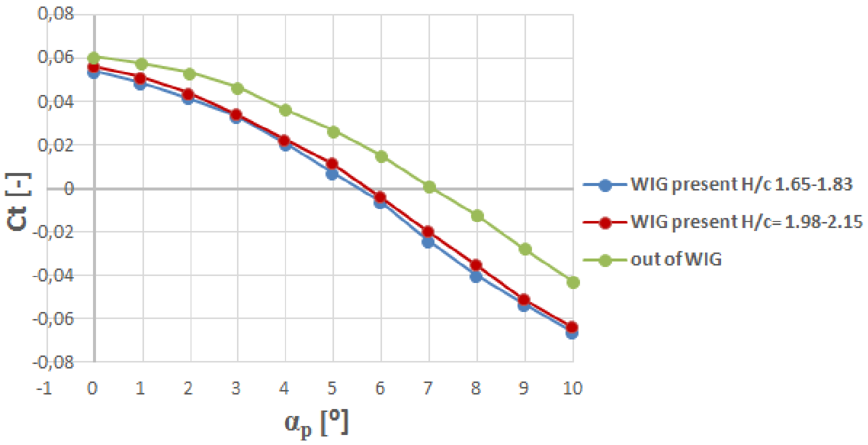

Fig. 4. Tangent force coefficient vs pitch angle

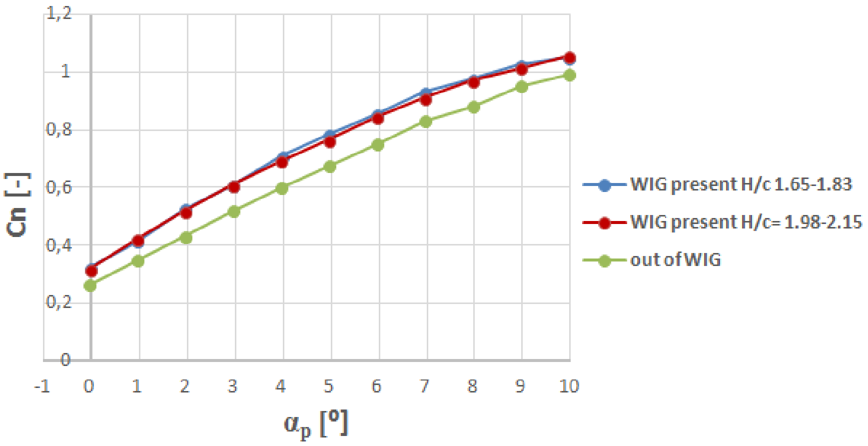

Fig. 5. Normal force coefficient vs pitch angle

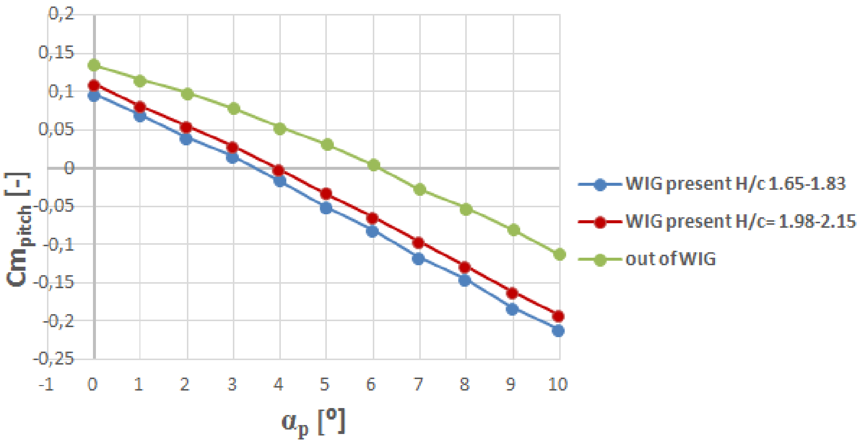

Fig. 6. Pitching moment coefficient vs pitch angle

A quantitative and qualitative change in the flow field in the measurement plane was observed in the PIV measurement results. For better representation a map of scalar velocity, magnitude and plot of the streamlines were presented in Fig. 7. One can notice higher momentum drop in the wake of the wing in case of ground presence (compare Fig. 7 left and right). Also the streamlines as well as velocity colour map revealed that in the case WIG effect the thicker wake influences more the velocity field in proximity of the horizontal stabilizer. The loss of the momentum of the flow may reduce the lift force and efficiency of the flight control surfaces in the tail region.

Quantitative reduction of the flow-flied velocity in front of the horizontal stabilizer is presented in Fig. 8. The velocity profile perpendicular to free stream direction was plotted for cases of free flight and WIG effect at angles of attack 0 and 10°. The nonintrusive measurement was performed ahead of the leading edge of the horizontal stabilizer. The velocity profile measurement line was marked in Fig. 3. In Fig. 8, it can be seen that the loss of the momentum is greater in case of WIG effect. An increase of the angle of attack results in substantial drop in velocity as well as thickening of the wake and lifting it to the level of the horizontal stabilizer.

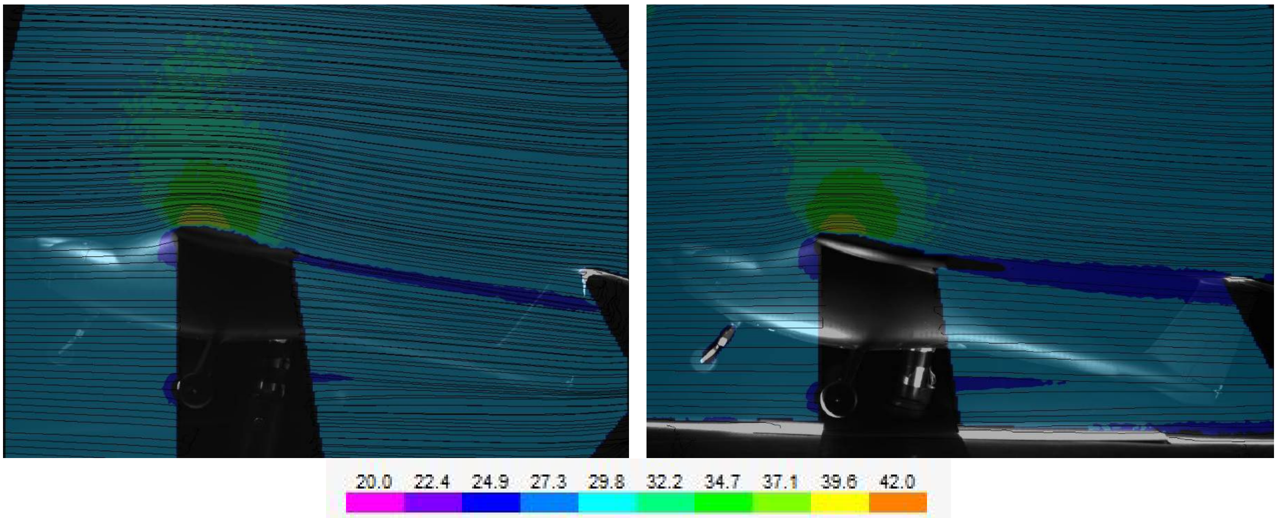

Fig. 7. The PIV pictures – without (on the left) and with ground imitation (on the right). $\alpha_p = 10°$. *Scale given in [m/s]*

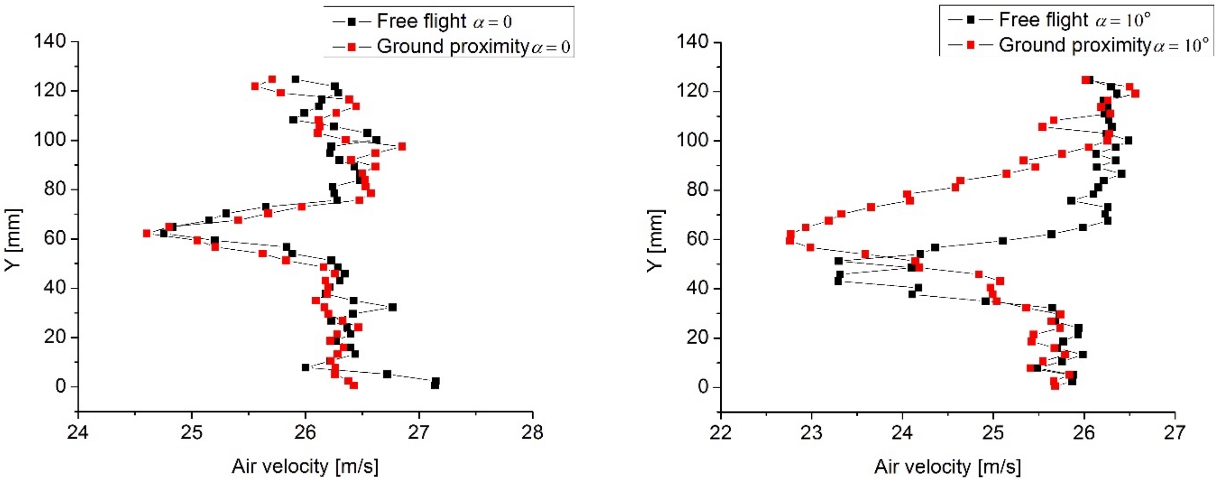

Fig. 8. The PIV results for velocity in wake behind the main wing: $\alpha_p = 0°$ *(on the left) and* $\alpha_p = 10°$ *(on the right)*

6. Conclusions

The ground proximity significantly influences on the aerodynamic characteristics of the aircraft. The greatest change concerns the pitching moment, which for the tested model was 30% lower than without ground effect. The ground proximity decreases pitching moment, which means a tendency to decrease angle of attack. This change is caused by increment of lift generated by horizontal stabiliser, which has two reasons. First is deflection of the flow upwards, caused by the ground. This deflection increases the stabiliser's angle of attack and is clearly visible in PIV results (Fig. 7). The second reason is that the horizontal stabiliser for high angle of attack is located close to the ground, which gains its lift due to the WIG effect. It is also a reason of change of the $dCm_{pitch}/d\alpha$ derivative.

The ground proximity also increases normal force and tangent force, up to 10% and 23% of the variation range, respectively. It can obviously improve the performance of the aircraft; however, usage of this effect may be difficult due to the safety of long flight on low altitude. Moreover, because an aircraft is flying more efficiently in proximity of the ground due to the WIG effect, it becomes airborne before reaching recommended take off speed. During landing, an aircraft tends to float above the ground. It has an important meaning for aircraft safety.

It should be noted that in case of the high-wing T-tailed aircraft, the wing wake in proximity of ground might cover the horizontal stabiliser for different pitch angle than out of the WIG effect. It may steeply change the efficiency of the horizontal stabiliser, while the airflow velocity in the wake is significantly lower, about 10% for the pitch angle of 10°. However, for the investigated aircraft this phenomenon does not appear, because of smooth change of the airflow speed in the boundary of wing wake.

It also should be mentioned that greater loss of the velocity in the wing wake and its greater width, in comparison of free flight case, means greater drag of the wing in the plane of PIV measurement (close to the fuselage, in 85% of tail span). Despite this, the total aircraft drag is decreased due to reduction of induced drag.

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