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Research paper

Wing-in-ground-effect craft: A case study in aerodynamics

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Abstract

A wing-in-ground-effect (WIGE) crafts can be deployed to fly by utilizing the ground effect, which is a natural phenomenon known to improve the efficiency of airplanes during take-off and landing approaches. In contrast, WIGE craft is not commercially viable for public transport mainly due to the difficulties in controlling its longitudinal stability. As an attempt to support the development of WIGE crafts, this paper presents a case study in aerodynamics based on certain published reports, specifically to reveal the available research data that are considered of interest and can be used as a lesson for further study and analysis. The wind tunnel procedure and testing, as well as numerical investigation of a WIGE craft, are applied and the results are then analyzed. The discussions are oriented in the perspectives of aerodynamics. Based on the tests and calculation, parameters concerning the ground effect as the WIGE crafts approaching the ground surfaces may be identified and hence their values can be determined. Thus, the static longitudinal stability may then be established and optimized for control of the WIGE craft.

Keywords: *wing-in-ground-effect; WIGE craft; aerodynamics; ekranoplan; hoverwing.*

1. Introduction

The wing-in-ground-effect (WIGE) crafts are defined as those that fly close to the ground surfaces by utilising the ground effect. This effect is known to improve the efficiency of airplanes during take-off and landing approaches. Most of available WIGE crafts show several common attributes that differentiate them from fixed-wing airplanes such as they have a low wing with large area and small aspect ratio, and a high fin with rudder and stabilizer attached to it at the utmost height [1]. The benefit of using WIGE is the extra lift generated that has been known since Wieselsberger published his work in 1921 [2]. Regular airplane pilots also experience this phenomenon during take-off and landing approaches, as the others who have flight tested it during the landing approaches [3, 4]. The ground effect is due to the presence of surface (ground or water) below the wing and this phenomenon increases as the wing moves nearer to the surface. The effect is in the increasing pressure below the wing that changes the overall flow field about it, thus enhance the wing lift-to-drag ratio.

Utilizing the ground effect has started around 1960s by the design and development of the WIGE craft (or ekranoplan in the Russian terminology) [5-7]. Back in 2002, Boeing Company has launched the conceptual development of the so-called *Pelican Ultra Large Transport Airplane*, which is purposely deemed to exploit ground-effect [8]. Some ground-effect researchers have claimed to invent improved methods by patenting their research outputs such as how to maintain altitude control [7], predict the dynamic ground effect forces [9] and also improve the aerodynamic characteristics [10]. The sheer complexity of WIGE craft requires that its development is initiated through systematic aerodynamic investigation and also guided by the principles of systems engineering, which might help to clarify the risk involved with the conceptual development and obtain much wiser knowledge as to whether the concept is worthy for further pursuit. From the commercial perspective, it is found that the larger the size of a WIGE craft, the higher its efficiency, with cautious note of the difficulty to develop and commercialize the full scale WIGE craft with the current technology [11]. The commercialization of the WIGE craft is obviously prone to arise through the operation of small-scale craft. With its success, larger scale WIGE craft can be further developed progressively later.

This paper presents a case study that supports WIGE development works by re-analyzing selected research works obtained from the published data as part of WIGE development process. However, it should be noted that the observation is limited to the experimental aerodynamics and computational efforts. The discussions will be oriented in the perspective of aerodynamics. Based on test results and calculation, all parameters concerning the ground effect as the WIGE crafts approaching the ground surfaces may be identified and their values determined. Static longitudinal stability may then be established and optimized for control of the WIGE craft.

2. Characteristics and system engineering of WIGE craft

Theoretically, WIGE craft has better lift-to-weight ratio compared to airplanes and lesser drag (hence increase in speed) than marine vessels. In practice however, WIGE craft faces inherent stability complications where changes in angles of attack, α and altitude, h from the surface are coupled. Designing this type of vehicle would also need to anticipate the restriction imposed by the physical laws due to movements in the air and sea, and conditions of its vicinity that it brings itself into conflict with some obstacles such as ships, buildings and raising lands. WIGE crafts must also have a durable hull structure to safely land on any surface and all their sensitive elements must be safeguard from salt and corrosions, or otherwise this would increase overall costs. The efficiency of WIGE crafts may be reduced due to possible design compromises, which may even make the utilization of this effect becomes questionable.

In airplanes, longitudinal stability achieved by choosing a suitable centre of gravity, and the generated lift is directly proportional to the angle of attack of the wing while position of the aerodynamic centre remains fixed. While flying at given cruising altitudes, any turbulence and wind gust occurrences would temporarily deviate insignificantly small magnitude compared to actual flight altitude and the resultant forces and moments exerting on the aircraft will restore it to its trim equilibrium. However, in WIGE craft, the ram pressure under the wing is directly influenced by coupled effect variation in the angle of attack, velocity, height and the roughness of the Earth’s surface. It must also fly with lift that varies for any change in both α and h. All these variables are unknown and thus the creation of flow field around the flying surfaces is unknown, which in effect dynamically alters the position of the aerodynamic centre from the original position. Obviously, the well-established notion is that some WIGE have inherent complications with static longitudinal stability conceptually. Thus far, no single method that is unanimously accepted on the safe control of the WIGE craft longitudinal stability has been established. Instead, there are two predominant schools of thought exist where problems of stability may be sorted out by sound performance design or by automatic control system, or perhaps both. Researches on WIGE crafts have been inclined towards using automatic control system [12-15].

Unlike airplanes, the International Maritime Organization (IMO) is the authority that sets rules governing WIGE crafts deployment. The requirements for WIGE craft that has been issued by IMO in 2002 read as follows: “*in the case of a failure of any automated equipment or device that makes a part of stabilization system, or its power drive, parameters of a WIGE craft movement must always stay within safe limits*”. Thus, the WIGE craft must have reliable aerodynamic and performance design that is intrinsically safe and complemented by an automatic control system such as the stability augmentation capability features. This will ensure an accurate information of the flight data and smooth management of the WIG craft navigation while also reducing the pilot's workload. The WIGE crafts that are dedicated to public deployment may be categorized as complex systems similar to airplanes and thus they should also be developed like airplanes and guided by principles of systems engineering [16]. By assuming one of the many system life cycle models, the development work might be divided into a series of stages that usually consist of:

- Stage I: Conceptual development (needs analysis, concept exploration and concept definition)
- Stage II: Engineering development (advance development, engineering design, integration and evaluation, certification)
- Stage III: Post development (production, operation and support)
- Stage IV: Disposal

Stage-I (conceptual development) will involve recognition of the market, exploration of the possible configurations and choosing the optimum configuration in terms of cost, efficiency and ease of use. Justification for choosing the approach is based on collective constitution of analyses, simulations and also functional designs. Stage-II (engineering development) corresponds to the validation of the unproven technology used, system functional design into hardware and software components implementation, and also the demonstration of the fulfilment of engineered system based on the user needs. It starts with system concept acceptance as an output from previous conceptual development and followed by decision to proceed with its engineering. This includes building prototype components, integrating them into the operating system and then evaluating it in a realistic operational environment [17].

3. WIGE craft: Aerodynamic investigation

Improvement in efficiency of WIGE craft is directly reflected by the increase in its ratio of lift-to-drag, which increases the flight range as proven by the Breguet range equation in Eqn. 1, where η_{pr} = propeller efficiency, c = specific fuel consumption, L = lift force, D = drag force, W_0 = take-off gross weight and W_1 = weight (assuming no fuel). This equation means that the range increases with better propeller, more fuel, more efficient engine and better lift-to-drag ratios.

$$\text{Range} = \frac{\eta_{pr}}{c}\frac{L}{D}\ln\frac{W_0}{W_1} \tag{1}$$

As a basic requirement for a good concept development, accurate value of lift-to-drag ratio is needed, which can be obtained from full-scale real flight tests or from wind tunnel tests, provided that the wind tunnel is big enough and shows excellent flow quality. In addition, a well-made model that conforms to the size and quality of the wind tunnel should be available. The size is here considered important because tests with too small Reynolds number would result in wrong aerodynamic coefficients. As reported in [1], a series of tests in the wind tunnel with a 4 m x 3 m test-section has been conducted on a model of > 2 m wing span, which represents 1:6 scaled model of the already defined eight-passenger WIGE concept as illustrated in Figure 1.

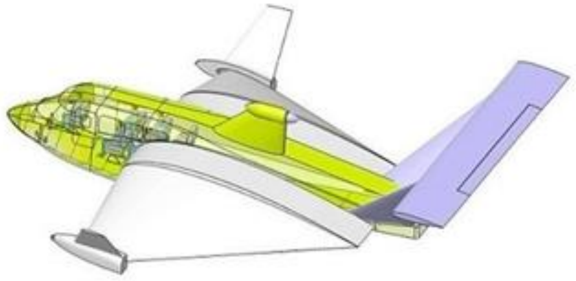

Fig. 1: WIGE in artist view as example [1]

The tests are run between 10 m/s to 50 m/s such that the Reynolds number of 3×10^6 based on the wing mean aerodynamic chord is attainable. The wind tunnel flow has been recalibrated to provide excellent tunnel flow qualities about velocities, pressures (static and dynamic), angularities, turbulence intensities and temperatures. The data matches well with the quantities measured from earlier calibration. Size and qualities of the wind tunnel and the model also satisfy the basic requirement. It is therefore justified to select data from the publication in Ref. [1] and use it with the following discussions.

3.1. Wind tunnel test procedure

A modular test model enables the test categorization through the integration of assembled model parts, starting from just a simple wing-body (WB) up to a complete model consisting wing, body, pontoon, nacelle, vertical and horizontal tail plane (WBPNVH). The model is mounted on the external balance by using two wing struts. The ground is modelled by the special ground board whose height with respect to model position is adjustable. The final test setup is shown in Figure 2 representing a complete model (without nacelle).

Fig. 2: Test model in the wind tunnel [1]

3.2. Wind tunnel test results

An example of applied visualization techniques using wool tufts that are attached to the upper wing, vertical tail plane and body surfaces is illustrated in Figure 3. The parameters of the model are fixed at the angle of attack, $\alpha = 4°$ and height, $h = 0.5$ m from the ground board. It is carried out at a velocity of 40 m/s and this flow visualization helps to validate the boundary layers along the whole upper surface of the wing.

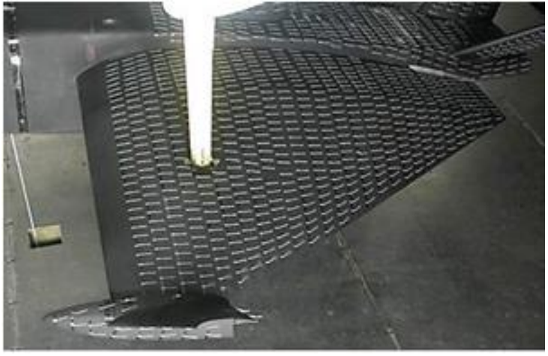

Fig. 3: Wool turf at $\alpha = 4°$, $V = 40$ m/s, $h = 50$ cm from ground board [1]

Furthermore, Figure 4 indicates that the reduction in downwash is inversely proportional to the rise of the lift slope as the separation of the model moves nearer to the ground board. Several equivalent heights of the dynamically scaled model above the ground board have been chosen: 0 m (almost), 0.3 m, 0.6 m, 1.5 m, 3 m, 4.5 m and 6 m (out of ground effect). The model's drag remains constant for around -2° to 2° and rises significantly for angle of attack, α of more than 3° as it moves nearer to the ground, which is shown in Figure 5.

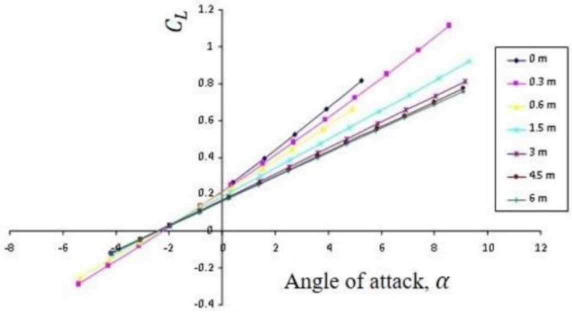

Fig. 4: C_L vs α, full configuration, WBPNVH. Various (equivalent) heights of the model above ground board [1]

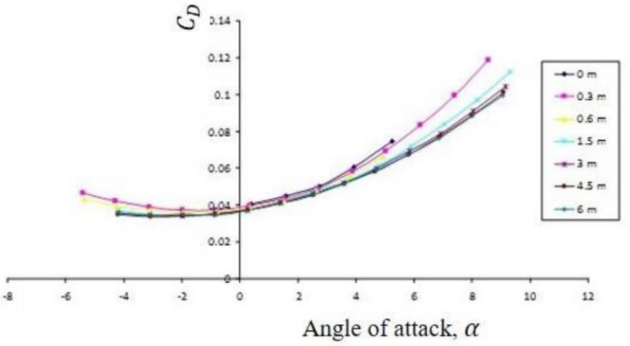

Fig. 5: C_D vs α, full configuration, WBPNVH. Various (equivalent) heights of the model above ground board [1]

The aerodynamic efficiency, C_L/C_D rises inversely proportional to reduction of the model height as illustrated in Figure 6. By making assumption of a setting $\alpha = 4°$ for cruise condition, a rise of 40% of total lift is achievable for current type of WIGE by increasing its aerodynamic efficiency.

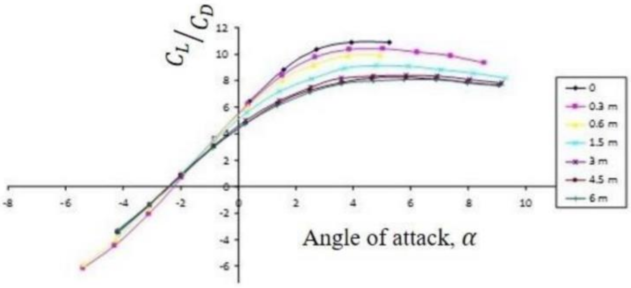

Fig. 6: C_L / C_D vs α, full configuration, WBPNVH. Various (equivalent) heights of the model above ground board [1]

In the meantime, the plot of pitching moment C_M against the angle of attack, α for full WBPNVH model is illustrated in Figure 7 with several equivalent heights of the model above the ground board similar to previous figures. From the graph, it can be seen that the model is longitudinally static stable. Normally, the range of angle of attack of the main plane is from 2° to 4° in most operational cruise condition of WIGE craft and within this range, the graph shows positive pitching moments for all heights. Therefore, WIGE crafts flying in this condition require the trimming of the elevators' pitching moments continuously, which means the automatic flight control is needed to reduce the flying crew workload as well as to automate and manage as many tasks as appropriate such that the crew role is a more of supervisory management [18].

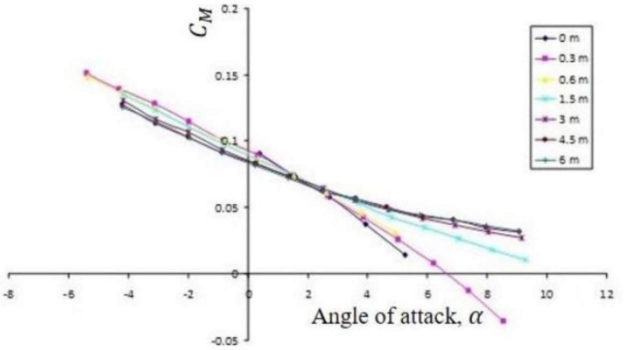

Fig. 7: C_M vs α, full configuration, WBPNVH. Various (equivalent) heights of the model above ground board [1]

Beside from the pursuit of having a complete model's aerodynamic characteristics, these tests have been also focused on determining the setting angle of the horizontal tail plane (HTP) optimally as this is important for longitudinal stability. By using prior measurement of pitching moment data, the model is modified with the purpose of getting α_{trim}. This can be done by having the wing angle of attack α within the margin of 2° and 4° via fine-tuning the moment due to pitching to nought. Normally, by adjusting the setting angle of the tail plane optimally, the problem would be settled. However, simulation of the effects of several appropriate setting angles of the HTP utilizing the numerical Vortex Lattice Method (VLM) must first be done before any physical modification can be applied to the model. Figure 8 illustrates the relationship of the moments due to pitching, C_M against angle of attack, αwith for four calculated HTP setting angles: i_h = -1°, 2°, 3° and 6°. This leads to the decision to modify the setting angle from its previous specification of i_h = -1° to the updated i_h = 2°.

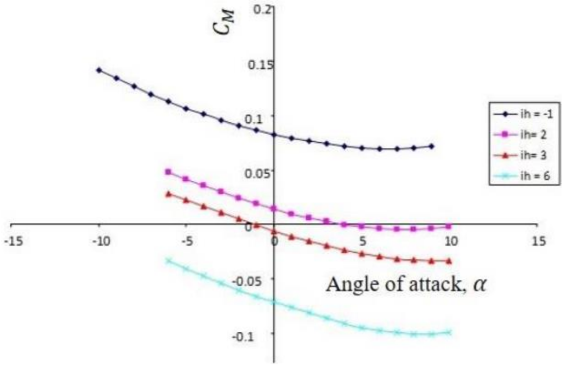

Fig. 8: C_M vs α, calculated by VLM for few setting angles, i_h of the HTP [1]

Figure 9 illustrates repeated tests on the modified model using the updated setting angle of the HTP in comparison to the previous setting, whereα_{trim} = 1.5° is now acquired. However, this updated value ofα_{trim} with regard to maximum C_L/C_D is not optimal, hence the best result should not be expected. Besides, since the current conceptual design includes propeller on top of the fuselage, α_{trim} is expected to be more negative. By redoing the wind tunnel test, a suitable i_h can be determined by optimal guessing.

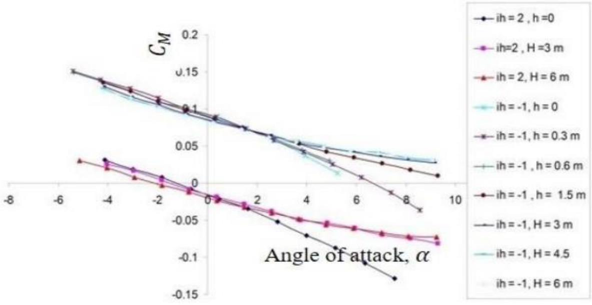

Fig. 9: C_M vs α, test results on modified model compared to the initial condition before modification [1]

3.3 Numerical investigation

By using commercial codes based on compressible-steady-viscous flow with Spalart-Allmaras turbulent model, the flow is calculated to acquire C_L and C_D as the term of height, h is normalized by the wing span, b. The calculation is limited to the following settings: α= 0°, speed M = 0.2 and height variation h/b = 0.05 to 1.69. The calculated values are presented in Table 1 and also in Figure 10 to Figure 12.

Table 1: WIGE Craft aerodynamic data (calculated)

h/b	C_L	C_D	C_L/C_D
0.0530	0.7730	0.0774	9.99
0.1060	0.6850	0.0759	9.03
0.1590	0.6382	0.0752	8.94
0.2120	0.6082	0.0750	8.11
0.2650	0.5887	0.0748	7.87
0.3180	0.5740	0.0746	7.69
0.4770	0.5498	0.0745	7.38
0.6360	0.5376	0.0744	7.22
0.7951	0.5309	0.0744	7.14
1.0601	0.5253	0.0744	7.06
1.5901	0.5209	0.0745	6.99

Figure 10 illustrates the distribution of C_L due to height variations. It is obvious that C_L becomes smaller with more separation distance between the WIGE craft and ground. The ground effect completely vanishes and its influence becomes zero at it flies at h/b = 0.8. Like C_L, C_D also demonstrates a similar asymptotic curve whereby it is becoming smaller as height increases, as shown on Figure 11, which has been proven by the test results on previous Figure 5.

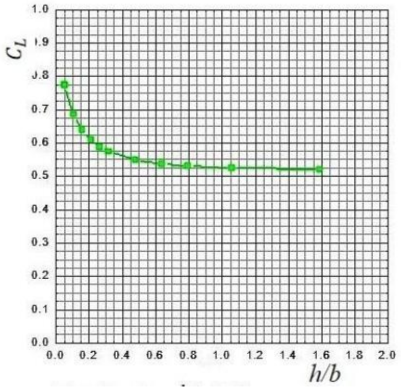

Fig. 10: C_L vs h/b [1]

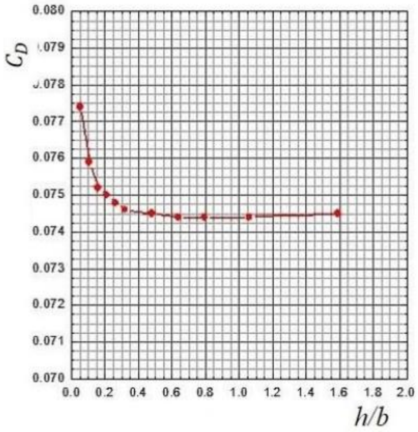

Fig. 11: C_D vs h/b [1]

Furthermore, Figure 12 illustrates C_L/C_D as function of h/b. This particular WIGE would benefit the ground effect if it has an altitude of 0.8 of its wingspan and lower.

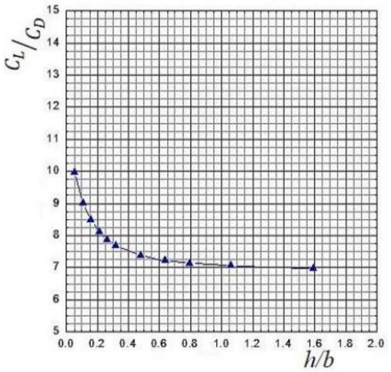

Fig. 12: C_L/C_D vs h/b [1]

4. Conclusion

Based on tests and calculation, the ground effect can be utilized by WIGE crafts nearing the ground surfaces in a range of h/b between 0.2 and 0.8. The static longitudinal stability may be refined by altering the HTP setting by trimming in the order of a few degrees. As apparent, the conducted test and calculation works described in previous section have not yet solved the design problems. However, the elaborated research works illustrate an example of important efforts of people, combining the experimental works and simulation methods. Assuming, that the problem with static stability is solved, the next step would be to research its dynamic stabilization. Once this is solved, an automatic pilot subsystem can be added that must comply with IMO regulation. By considering the systems life cycle model and realizing that there is no WIGE craft serving for public transport and there is no consensus in controlling the longitudinal stability, plus the available WIGE crafts are only mostly prototypes, demonstrators or test flight vehicles, one may categorize that the status of the current WIGE's development remains stagnant at the stage-I, which is still at the conceptual development.

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