Numerical Study on the Section Design of a Wing in Surface Effect

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Abstract: A Wing-In-Ground (WIG) craft or also known as Wing-In-Surface Effect (WISE) craft is a marine transportation system equipped with wings which enables it to remain airborne just above the water surface. A WISE-craft harness ground proximity effects to increase aerodynamic loading and efficiency. It fills the technological gap between common aircraft and ships. A WISE-craft operates at much higher speeds than ships and more efficiently than aircraft. Another distinct advantage of a WISE-craft is its ability to take off anywhere from the sea surface without the need for a landing strip. Due to its terrific and unique features, WISE-crafts serve as a promising choice of fast, safe and efficient platform for the next generation of marine transportation systems. The objective of this work is to investigate the aerodynamic characteristics of the section design of the wing, for the purpose of achieving improved WISE-craft designs.

1 INTRODUCTION

Airplane wings usually produce higher lift near the ground at a moderate angle of attack, known as a positive ground effect. Thus, craft wing-in-ground-effect (WIG) is designed to fly near the ground using positive ground effects (Rozhdestvensky, 2006). Compared to ships, WIG craft has lower drag, higher speed, and lower fuel consumption, and its cruise speed is less affected by sea states. Compared to comparable size aircraft, a WIG craft has a higher lift-to-drag ratio, lower thrust, wider flight range, and greater load. On the other hand, very curved wings produce downforce close to the ground. In this case, closer to the ground, the greater the downforce; this is known as the "neglect-ground-effect". Race car wings use the neglect ground effect to improve the race car's running speed and maneuverability.

To avoid collisions with buildings and hills, WIG crafts usually cruise on the water surface, including lakes, rivers, and oceans. There are often waves on the surface of the water due to the wind and other disturbances. Aerodynamics of a WIG craft that flies over different wavy surfaces than flat surfaces because of the wavy surface change the nature of the airflow around the WIG craft. However, in the literature, the majority of soil effects aerodynamic studies focus on two-dimensional airfoils or three-dimensional wings that fly over flat ground. WIG is identical to the wing in surface effect (WISE), and in this paper, the author uses the term WISE because our application is also on the surface.

For a precisely designed lifting surface, the effect of the surface brings about augmentation of lift for smaller surface clearances. Wing profiles with an almost flat lower surface (classical example is NACA 4412) produce an optimum surface effect (SE) (Sun and Dai, 2015). Profiling of the foil for preferable longitudinal static stability usually results in lower lift coefficients which are not certainly disreputable for cruise flight. For a given wing area the lift is larger for a larger aspect ratio wing. Flaps are not as efficient in SE as they are out-of-surface effect. The drag is majority determined by its induced vortex drag component and it depends on the reciprocal relationship of the chord, span and surface clearance, etc.

Experiments and theory show that for a fixed pitch angle, in some cases (chord-dominated SE) the drag increases as the wing moves closer to the surface. In another case (span-dominated SE) the drag decreases with decreasing surface clearance. In all cases, for a properly designed lifting system, the lift-to-drag ratio tends to increase with the decrease of the surface clearance. Also, in all cases for a properly designed lifting surface, the drag decreases with decreasing surface clearance for constant lift. The fact that near the surface the lift-to-drag ratio increases both with the

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increase of the aspect ratio and decrease of the surface clearance provides more flexibility in selecting optimal design solutions than for the conventional airplane.

WISE crafts typically cruise at small to moderate angles of attack over the water surface, but they occasionally fly at large angles of attack when they need to climb to avoid an emergency obstacle or are affected by random gusts and water waves. Therefore, for safe flight operation of a WISE craft, it is important to study the aerodynamic performance of WISE crafts. There are several major situations that need to be considered for the case of a WISE vehicle operating in a sea environment:

- floating and drifting in waves,
- take off in waves,
- landing in waves, cruise flight over waves, the occasional impact of the waves and, in an exceptional case, of rogue waves upon the vehicle and its elements.

In the current research, a numerical study was carried out to investigate the aerodynamic characteristics of the wing in surface effect on the section design of the wing. The study will hopefully be achieving improved WISE-craft designs. In this study, finite element software is used to simulate the flow around the wing of WISE. The various design of wing sections are investigated and the flow around the wing is analyzed.

2 LITERATURE REVIEW

2.1 History of WISE

Wing-In-Surface Effect (WISE) craft is a marine craft equipped with wings which enables it to remain airborne just above the water surface. WISE transportation vehicles have attracted considerable attention in view of their potential civil and military applications. Some of the benefits of WISE-craft include a high-speed operation (compared to traditional marine craft), improved payload and aerodynamic efficiency (Fuwa and Hirata, 1993).

One of the earliest WISE craft which contributed significantly to WISE-craft technology was the Russian Ekranoplan. A series of Ekranoplan, namely the SM and KM series, has been successfully constructed by Russian engineers. They all share some common characteristics, such as an aircraft-like configuration (wing, fuselage, and tail), a rectangular wing with low aspect ratio, together with a large and high tail for longitudinal flight stability. One obvious feature of the Ekranoplan is the use of Power Augmented Ram (PAR) to assist takeoff by directing the exhaust air from the engine over the main wing. Another type of WIG-craft, which is characterized by a Reversed Delta wing and a high tail configuration, has been designed by Lippisch, a German aerodynamicist. The Lippisch type of WISE-craft is the only one that has proven to be inherently stable in surface effect (SE) (Barber and Hall, 2006).

The WISE vehicle is a promising means of transportation since it utilizes the favorable ground effect (Rozhdestvensky, 2000). It lies between a seagoing ship and an aircraft in terms of its characteristics. It is generally faster than the ship and has much lower fuel consumption than an airplane. The WIG craft would have application wherever there are: (a) significant spans of overwater operations; (b) inadequate aircraft operational bases to support airline operations; (c) beaches or simple port unloading facilities for roll on-roll off operations. WISE craft characteristics exceed those of ship and aircraft because of it can carry greater than aircraft payloads over significant distances at general aviation aircraft speeds (Yang et al., 2015). By now, a number of WISE crafts have been developed and manufactured, and even some have been in commercial operation (Kubo and Rozhdestvensky, 1997).

2.2 WISE as an Overseas Transportation

Only two available modes of overseas transportation are currently available: aircraft and ships. However, the speed of conventional ships is less than 50km/h (large container ships), while that of air-freighters is over 800km/h. Meanwhile, the freight cost of an airplane is ten to twenty times higher than that of a container ship on the basis of weight. There are large gaps in speed and fare in which these two forms of transportation are subject to operational inefficiency. Consequently, cargo and passengers whose demand for speed and price coincide with this gap are forced to choose a mode from these two extremes of air- and sea-transportations. This leads to the non-optimal and non-efficient use of transportation resources. Meanwhile, the economical service speed of WISES, aided by surface effect, is from 200km/h to 500km/h, which is suitable for meeting potential transport demand around this gap (AKIMOTO et al., 2010).

The construction cost of a WISES is expected to be less than that of an airplane of the same size. WISES design requirements and regulations are moderate in comparison to those governing airplanes because WISES is categorized as a ship. The low aspect ratio and thick wing of WISES are easy to construct. Furthermore, a pressurized cabin is unnecessary, thus reducing fatigue strength requirements. For WISES navigates only in very low altitude, its governing regulations are those of ships. Therefore, requirements of safety, structural strength and pilot trailing of WISES are lighter than in aviation laws. It differentiates WISES from seaplanes those tend to be high-cost airplanes.

Although a WISE appears similar to an airplane, it has different properties from the standpoint of commercialization. The ship experiences hydrodynamic loads while taking off from and alighting on water. Although there is no explicit limitation to the length of water runways, the speed at take-off and alight has a great influence on the ship's economy. As acceleration before take-off occurs on water, the required power of the vehicle is nearly proportional to the cube of take-off speed. In addition, the maximum hydrodynamic load of the ship is proportional to the square of the speed. Therefore, a decrease in take-off speed allows for a smaller engine and lighter structural weight of the vehicle. Slow take-off and alighting (STOA) capability is important for reducing both the construction and operational cost of the ship (KAWAKAMI and AKIMOTO, 2006).

2.3 Experimental and Numerical Study on WISE

The aerodynamic characteristics of 2D airfoils and 3D WISE have been investigated both experimentally and numerically by other researchers (Fuwa and Hirata, 1993). The general conclusion is that there is a reduction in induced drag and an increase in lift as the ground is approached. As a result, both aerodynamic efficiency and aerodynamic loading are increased due to ground proximity effects. Pioneer researchers such as Kumar (1972), Irodov (1974), and Staufenbiel and Schlichting (1988) have analyzed various aspects of WISE craft longitudinal stability.

Ho et al. (2008) also investigated the effects of end plate (numerically) on a highly cambered aerofoil. Aerofoil shape optimization underground effect had been carried out by Moore et al. (2002). Studies have shown that the ground has a significant influence on the pressure distributions along the wing surface. As a WIG vehicle moves forward, the speed of the oncoming air gradually decreases under the lower wing surface, and dynamic pressure changes to static pressure. This increased pressure is called an air cushion or a ram effect, and it necessitates a longer runway for landing.

Technical feasibility of WISE vehicles (possibility to develop lifting systems taking advantage of SE and able to perform stable flight in proximity to an underlying surface) has been proven both through model experiments and full-size trials of prototypes.

Different aerodynamic configurations have been developed and examined, each of them showing advantages and disadvantages from the viewpoint of specific applications. A tendency is observed for configurations to evolve into all-wing (flying wing) or composite wing schemes, the latter being particularly advantageous from the viewpoint of efficient take-off, aerodynamic (economic) viability in cruise and a wider range of pitch stability.

Extensive wind tunnel tests were carried out in the closed-type wind tunnel at Pusan National University. Lift and drag forces and the pitch moment of NACA6409 was measured as several aerodynamic parameters such as the aspect ratio (AR), the angle of attack (α), ground clearance (h/c) and endplate shape were varied. In addition, the smoke trace technique was employed to visualize the flow pattern around the wing during the ground effect. This experimental study presents how the aerodynamic performance of NACA6409 during the ground effect is influenced by various design parameters (Jung et al., 2008).

In 2006, Al-Atabi (2006) fitted three small lifting surfaces to the tip of a NACA0012 wing similar to that of the wing tip feathers, the tests show that tip-sails could decrease the induced drag, increase the longitudinal static stability and break the tip vortices. In 1977, Withers and Timko (1977) recorded motion picture of black skimmers flapping and skimming over a water surface by the camera. The flight velocities and the wing-beat frequency were achieved by analyzing the films. The conclusion is that ground clearance has a great effect upon the foraging energetics and daily energy balance of skimmers. The experimental results of Ground Effect of a wing mounted with tip sails are introduced by Sun and Dai (2015). The study has evaluated the flow control efficiency of primary feathers to the wing of a pelican skimming over the water surface. Compared with a NACA4412 prototype wing, the experimental results show that, for the same ground clearance, the lift coefficient of the tip-sails wing increases significantly and the stalling angle of attack decreases, the drag coefficient keeps nearly unchanged at a small angle of attack (AOA) and decreases obviously at higher AOA.

Figure 1: WISE (Trimaran) Craft Model

Table 1: Foil Shapes Modification on WISE's Wings

No.	*Foil Shape*
1.	NACA 0006
2.	NACA 4412
3.	NACA 6409

3 COMPUTATIONAL FLUID DYNAMIC

3.1 Geometry and Modelling

Prior to the CFD analysis carried out for prediction of the lift force, 3D hull form of the trimaran vessels was generated with CAD software. The trimaran vessels are designed to have ailerons on her starboard and port to help her maneuvers. In addition, in the tail section of the vessel is given a pitching stabilizer which is useful to help the vessel in the process of taking off and landing. The vessel's propeller is located on the top of the vessel and is supported by a rudder on the back of the vessel. The WISE craft 3D model is shown in Figure 1.

In this paper, the 3D hull forms were developed with 3 (three) modifications of foil shapes on her main wings, as in Table 1. The modifications on her wings are expected to minimize the craft's resistance, thus increasing the lift forces. At the end of the research, the most optimum wing shape will be selected to be made a prototype.

3.2 Mesh Generation

The next stage after the 3D model is created is to divide the model geometry into small elements (triangles, tetra/mixed, hexa-dominant) called a cell. These cells form a unity called mesh or grid due to their configuration which looks like mesh, thus this process stage is commonly called as meshing. Mesh is of considerate importance for computational purposes. The mesh size of the vessel can be seen on Figure 2 below.

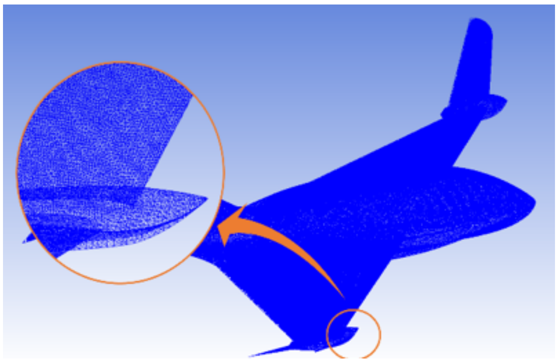

Figure 2: Mesh Size of the Trimaran Vessel

3.3 Boundary Condition

The model that has been meshed then will be set up appropriate boundary conditions to run simulation of free flight. The boundaries that were created namely: inflow, outflow, wall, top, and bottom. After the boundaries have been made, each boundary will be defined as can be seen on the Table 2 below.

Table 2: Boundary Condition

Boundary	*Type*	*Conditions*
Inflow	Inlet	Normal speed 16.2 knots
Outflow	Outlet	Static Pressure 0 Pa
Wall	Wall	Free slip wall
Ground	Wall	No slip wall, smooth wall
WISE	Wall	No slip wall, smooth wall

4 COMPUTATIONAL RESULTS AND ANALYSIS

4.1 Lift Force

The lift forces of the three WISE crafts are presented in Table 3 with respect to varying the foil shape of her main wings at her service speed, i.e 16.2 knots. As it can be seen on the table, the highest lift force was generated by NACA 4412, followed by NACA 6409, and lastly, NACA 0006 placed at the bottom.

Table 3: Boundary Condition

Boundary	*Type*	*Conditions*
Inflow	Inlet	Normal speed 16.2 knots
Outflow	Outlet	Static Pressure 0 Pa
Wall	Wall	Free slip wall
Ground	Wall	No slip wall, smooth wall
WISE	Wall	No slip wall, smooth wall

4.2 Surface Pressure

Figure 3 up to Figure 5 provided an overview of the total pressure distributions around the three crafts with the same speed and height in cruise. WISE with NACA 4412 wing foil shape indicated that higher negative pressures were recorded along the vessel's wing surface. Higher negative static pressure, corresponding to the reference static pressure from the inflow, was found near the leading edge of the wing. This results in an increase of lift forces on the wings of the vessel.

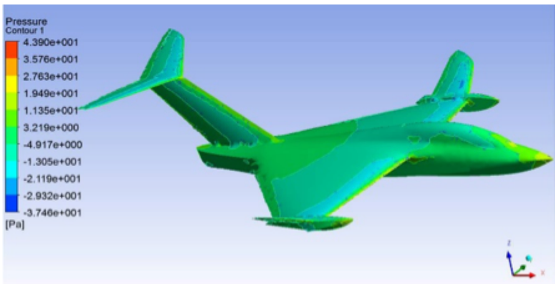

Figure 3: Surface Pressure Distribution on WISE [NACA 0006]

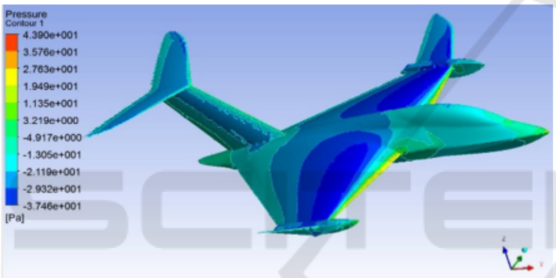

Figure 4: Surface Pressure Distribution on WISE [NACA 4412]

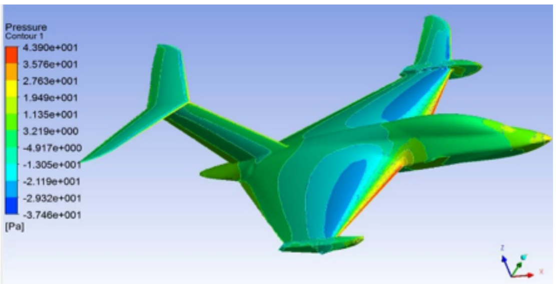

Figure 5: Surface Pressure Distribution on WISE [NACA 6409]

4.3 Flow Visualization

Figure 6 up to Figure 8 show the flow pattern around the three WISE crafts at the speed of 16.2 knots which represents service speed.

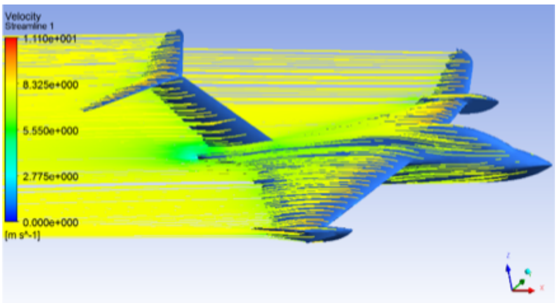

Figure 6: Flow Patter around WISE [NACA 0006]

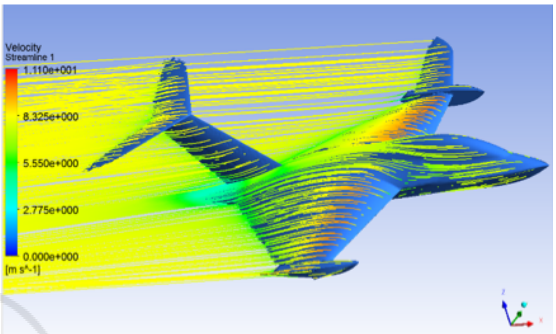

Figure 7: Flow Patter around WISE [NACA 4412]

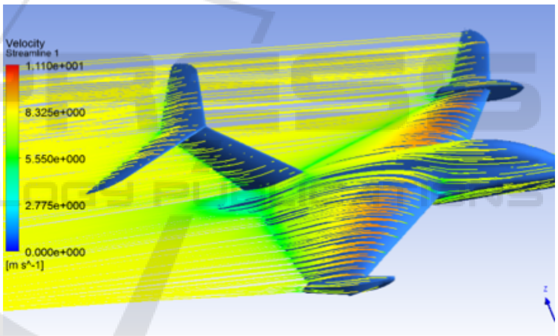

Figure 8: Flow Patter around WISE [NACA 6409]

5 CONCLUSIONS

A detailed numerical investigation of the aerodynamic characteristics of a WISE craft for various design of wing section using NACA series, it can be summarized that NACA 0006 gives the lowest lift forces and the design of NACA 6409 generate the highest lift forces. Therefore, it can be concluded, design of wing section using NACA 6409 more recommended for the WISE craft in speed 16.2 knots.

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