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AERONAUTICAL ENGINEERING I

Wing in Ground Effect (WIG) aircraft Aerodynamics

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Project assessment

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Group mark (please do not write anything in the table below)	
Criteria	Mark (total 100)
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Executive Summary

The wing in ground (WIG) effect has effectively been known to aviators for as long as man made aircraft have existed. The WIG effect is a phenomenon that creates an increase in lift experienced by an aircraft as it approaches the ground for landing, when vortices of air become trapped between the wings of the aircraft and the ground creating a cushion effect. An inherent danger of this effect is that the additional lift can change the angle of attack of a landing craft, causing longitudinal (pitch) instability. If not properly corrected (e.g. in the hands of an inexperienced pilot), the potential exists for stall to occur, which could result in the aircraft crashing with possible casualties. The ground effect is widely seen as a good thing, and most aircraft can benefit from the ground effect in the form of a better landing (helicopters are affected by the ground effect as well). The additional lift provided by the ground effect reduces demand on the engines of an aircraft and power needed in order to stay airborne, thus making it more efficient. The knowledge that ground effect flight is more efficient than traditional flight has lead people to develop craft that exploit this benefit by being designed to fly close to the ground. Development of WIG craft spans roughly over the past 50 years, ranging from small scale recreational craft, to large scale military craft, yet such craft have not become successful mainstream products. This is largely due to the limitations present in existing WIG craft designs, such as the high maintenance nature of having exposed engines in close proximity to the sea, which reduces reliability. Such factors have previously lead to a withdrawal of military funding for research and development in this area, across all major countries that were once rigorously involved in this research. Despite this, the potential still exists for WIG craft design to achieve the functionality required to become successful in niche areas such as high speed transport rather than warfare.

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1. Introduction

The wing in ground (WIG) effect is a phenomenon that affects all aircraft in some way, due to vortices of air that become trapped between the wings of an aircraft and the ground (when the aircraft is near to the ground). It is important to note that ‘ground’ may refer to not only land, but also water, ice, snow and sand. The effects of the wing in ground effect can be beneficial or detrimental to the aircraft. Various craft have been designed specifically to utilise the benefits of this ground effect, and hence are not actually regarded as ‘aircraft’. Although development of WIG craft has taken place over many decades, the technology has not progressed to the point where such craft can become a mainstream commercial success, due in part to early design inefficiencies and a lack of government funding for research and development in this area worldwide. However, it is still widely believed that the potential exists for WIG craft to have practical applications.

This report investigates the theory, history, applications, advantages and disadvantages of the wing in ground effect in aircraft as well as the current state and future of craft designed for ground effect flight. This report will also analyse the key design principles of specialised WIG craft and their operation, as well as case studies on the most significant WIG craft to have emerged since development of these craft began.

Figure 1: Vortices on the tip of a wing [33]

2. History

For as long as man made aircraft have existed, aviators have been aware of the increase in lift (or cushioning effect) experienced by an aircraft as it approached the ground for landing. The Wright brothers unintentionally used this effect to fly further when close to the ground, and to perform what was described as a 'pancake landing', where a sudden loss of lift upon landing resulted in the aircraft landing flat on the ground. These observations led to studies in the early 1920's, in order to gain a formalised understanding of this phenomenon, dubbed the 'ground effect' or 'wing in ground (WIG) effect' [7].

In 1921, a German scientist named Carl Wieselsberger released a study demonstrating a theoretical understanding of the ground effect in aircraft, explaining the relation between ground effect and planar wing performance, as well as the resulting increase in lift to drag ratio experienced by the aircraft. This study was widely accepted and still is today. It was determined experimentally, that the effects of the ground effect such as the pancake landing were due to the geometry of the wings of the aircraft in relation to the ground. With this knowledge it was possible to reduce the adverse effects of the ground effect [7].

Soon after the wing in ground effect and its potential benefits were understood, several countries began developments with the aim of exploiting these benefits. By flying low and utilising the increased lift from the ground, some aircraft were able to increase fuel efficiency, thereby allowing them to fly further with less power. In 1929, the Dornier DO-X seaplane was able to cross the Atlantic with a by flying close to the sea and was also able to carry a greater payload. It is likely that the Dorniers ability to carry out transatlantic flight provided motivation for many subsequent efforts to design craft with the WIG effect in mind. The increased efficiency provided by the ground effect was also helpful to numerous bombers during World War II, where damaged fighters could reach their otherwise out of range base by flying close to sea level [31].

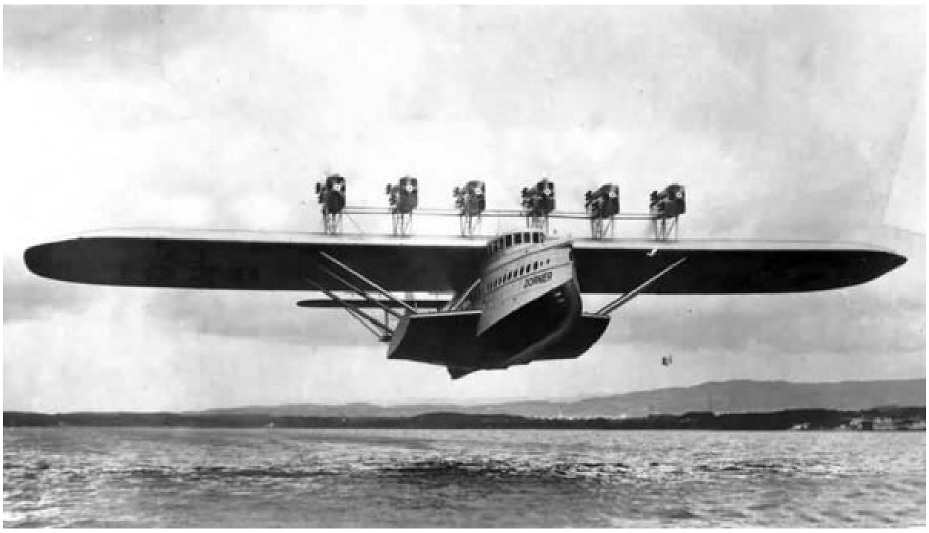

Figure 2: The transatlantic Dornier DO-X Seaplane 1929 [31]

It is believed that the first functional ground effect craft was developed during in 1935 by a Finnish engineer named Toivo J Kaario. The craft was named the 'Aerosledge No. 8', but did not receive enough funding for further development. The USSR and the USA were among the first countries to develop experimental aircraft during the early 1960's that made use of the WIG effect, while Germany began developing in the late 1960's. It was the USSR however, that had by far the largest presence in this area of research during this era, through military funded development. Most of today's knowledge regarding WIG craft design has come from the 1960's, as well as history's most iconic WIG craft. Despite flaws in the design of the early WIG craft, it became clear that the potential existed for practical applications [22, 23].

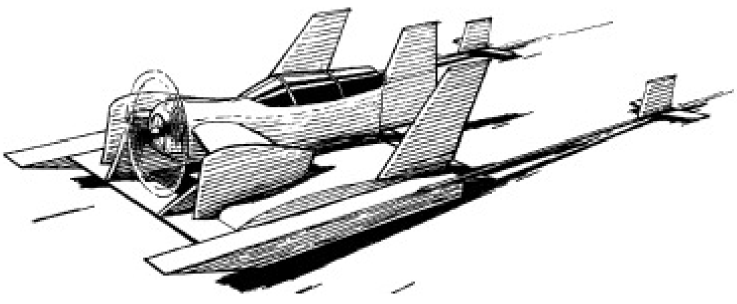

Figure 3: The Aerosledge No. 8 1935,
believed to be the first functional WIG craft [22]

Soviet WIG craft were known as ‘ekranoplan’, meaning ‘low flying plane’ in Russian. The ekranoplan projects were lead by designer Rostislav Evgenievich Alexeyev. The soviet built ekranoplans were among the largest WIG craft ever built. These craft are also referred to as PAR-WIG (power augmented ram wing in ground) craft, by incorporating a ram wing planform and engines to provide power assistance for take off and landing [7].

In 1963, the KM (otherwise known as the ‘Caspian Sea Monster’) was built, and is the largest, most notorious ekranoplan prototype to have been built. Following the KM, various other ekranoplan prototypes were developed, followed by several production models. The eight engines at the front of the craft provided the required take off lift, but were not used once level flight had begun. This was an example of power augmentation to overcome water drag [7].

Figure 4: The ‘Caspian Sea Monster’ Ekranoplan model KM 1963 [31]

Also built in 1963 was the small single seat Collins X-112 ‘Aerofoil boat’, designed by German Scientist Alexander Lippisch and built in America. It was built for the purpose of demonstrating stable ground effect flight. The craft was considered successful and inspired further development into the German built X-113 (1970) and the larger six seat X-114 (1977) prototypes, both of which performed successfully. The X-113 was able to fly out of ground effect, to an altitude of 800 meters, but this required full power from the engine and hence, excessive fuel consumption. This was found to be an inherent weakness in all WIG craft when flying out of the ground effect. Plans for larger military craft existed, but there was insufficient interest and funding. Development ceased after the X-114 crashed, due to pilot error [3].

Figure 5: The single seat Lippisch X-112 [31]

Figure 6: The Lippisch X-113 [31]

Figure 7: The sit seat Lippisch X-114 [31]

Numerous studies and research activities were undertaken in the USA to investigate the effectiveness and feasibility of WIG craft for military applications; however they did not result in the actual development of any operational models. It was recognised that WIG craft suffered from longitudinal or pitch instability. Furthermore, US testing showed that WIG craft had less than ideal performance as a result of factors regarding take off and landing. America eventually ceased military funding for WIG craft, and the X-112 was sold to a German company [7].

In 1979, the Soviet built A-90 Orlyonok became one of the first WIG craft to be used for operational service for the Soviet Navy. Designed in 1974, only five of the intended one hundred and twenty models were built, and were designed to quickly transport large payloads, such as troops and assault vehicles, thus replacing the slower sea vessels that were currently in use for such purposes. Of the five that were built, one was a model for static testing, one crashed during a demo flight in 1975, and another crashed during service in 1992, killing the crew. The Orlyonok was withdrawn from service in 1993 [27].

Figure 8: The Orlyonok A-90 [31]

In 1987, the Lun-class Ekranoplan was introduced by the USSR. This craft was equipped with missile launchers, designed for anti submarine warfare. The intended advantages were the ability to carry large payloads, to travel at high speeds with low observability and with no need for an airport. The MD-160 was the only model in the Lun-class range. It was trialed for three years but was never used in operation [14].

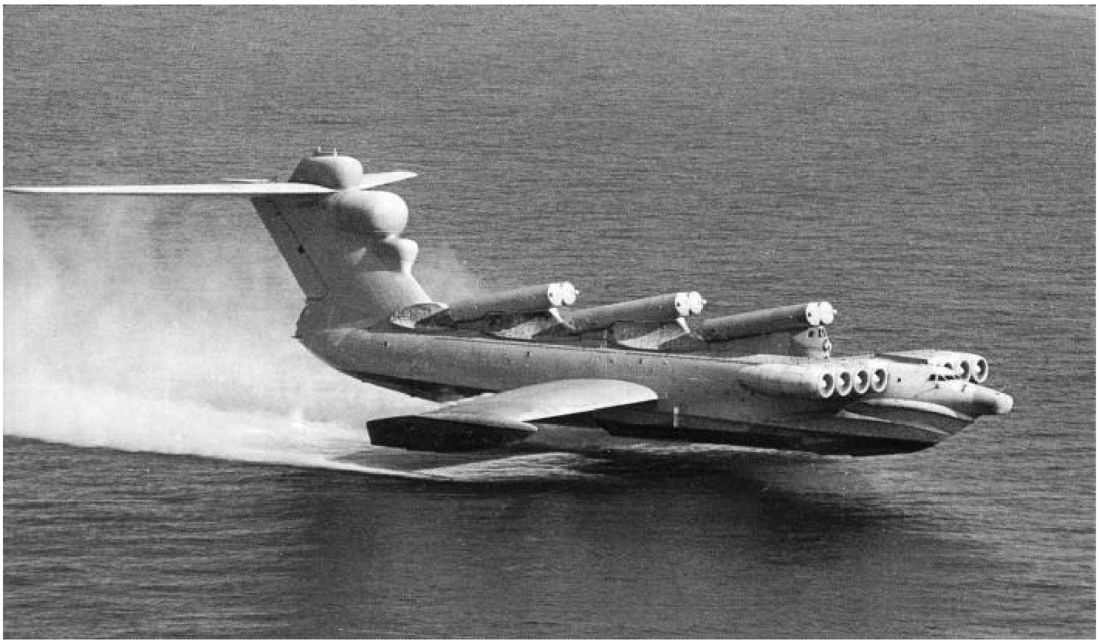

Figure 9: The missile equipped Lun-class Ekranoplan 1987 [7]

Since the 1980's, and with the fall of the Soviet Union in the early 1990's, the scale of research and development into WIG craft has decreased, and the focus of development has shifted toward smaller sized craft, for civil and recreational applications (e.g. heavy cargo transport, ferries etc), rather than military applications. Seating capacities for these craft generally range from two to ten. The more recent innovations in this field have come from the USA, Germany, Russia, while some development has occurred in China, Japan and Australia, where development initiatives have been spearheaded primarily by aviation enthusiasts and academics. To this day, WIG craft have not been a commercial success, but much work is still going into the development of these craft so that they one day become mainstream [7, 24].

3. Theory

There are many different shaped bodies which can produce lift; however the most efficient design so far is the wing. Wings generate lift because the movement of the wing through air results in a higher static pressure on the lower surface than on the upper surface. This difference in pressure results in an upwards force known as lift which allows the aircraft to overcome its weight force acting downwards.

Under most circumstances, aircraft fly in a free stream where there are no boundaries restricting the air movement. WIG aircraft however make use of the "ground effect", which is the name given when a boundary occurs below and close to the wings lower surface. In practice, this boundary is the Earth's surface either water or land.

The presence of a boundary close to a wing results in increased static pressure on the lower surface hence increasing the lift generated. As the efficiency of a wing is determined by the lift to drag ratio, the efficiency of a wing increases due to the ground effect. It is therefore possible to design craft which fly at low altitudes so that they are in close proximity of the Earth's surface and can take advantage of the ground effect.

3.1. Theory of Flight

3.1.1. Lift and Drag

In order to explain how WIG aircraft differ from conventional aircraft it is necessary to first define a few elementary aerodynamic concepts. As a wing moves through air a resultant force in generated. This resultant force can be decomposed into lift (perpendicular to the free stream velocity) and induced drag (parallel to the free stream velocity). Other forms of drag are also present which are the result of friction as the aircraft moves through the air and are referred to collectively as parasitic drag. The total drag is the combination of both parasitic drag and the induced drag.

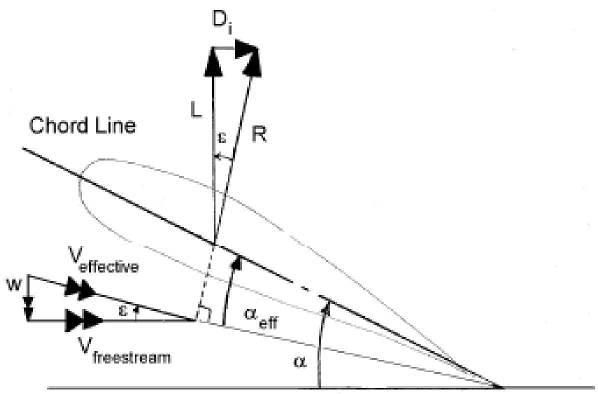

Figure 10: Lift and Drag of an Aerofoil [7]

It is common in aerodynamics to non-dimensionalise lift and drag and hence describe them in terms of coefficient of lift and coefficient of drag. This is because lift and drag are dependent on numerous factors such as the geometry of the aerofoil, the air density (dependent on height) and the velocity of the craft. Through using the coefficients of lift and drag, the velocity and air density dependence is eliminated and hence lift and drag can be discussed in terms of geometry alone.

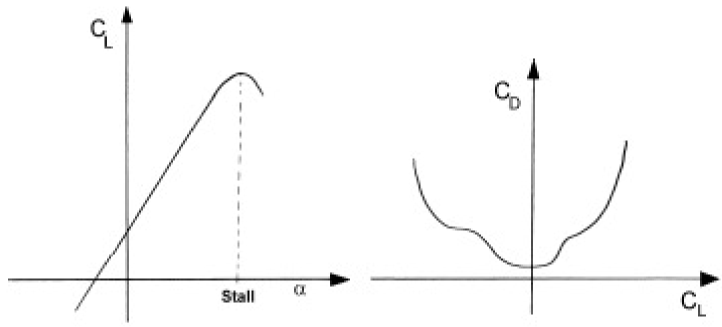

Figure 11: Aerodynamic Relationships [7]

3.1.2. Downwash

Conservation of momentum requires that the air flow must change direction before it reaches the wing and after it leaves the wing. As the wing gains momentum in the upward direction, the air must gain an equal amount of momentum downwards. This distortion of the flow is called downwash.

Downwash can be represented as a vertical velocity component of the free stream velocity. Its effect is to change the incidence of the velocity vector at the wing resulting in an effective angle of incidence which is less than the angle of incidence in free stream flight. The resultant force is dependent on the angle of incidence and is rotated clockwise due to the downwash which causes a decrease in lift and an increase in drag.

3.1.3. Geometry

The geometry of the aerofoil being used can significantly alter the aerodynamic characteristics with a variation in angle of incidence. This gives rise for the need of different aerofoil sections depending on the individual operating requirements of aircraft. For example, the speed at which aircraft are intended to operate at will determine the thickness of the aerofoil used. At slow speeds thick aerofoils will be used and at fast speeds relatively thin cross sections.

Not only is the thickness of the aerofoil important but also the aspect ratio of the wing. The aspect ratio is determined by the ratio of the wing span divided by the chord length and gives a measure of how much lift is generated at the wing tips. This is important because losses in lift are greatest at the wing tips due to vortex shedding therefore the higher the aspect ratio the more efficient the wing will be due to smaller losses in lift. In theory, very long wings are the most efficient however they are not practical because of the high stresses which are imposed upon them during flight.

3.2. Ground Effect

Ground effect is caused by the presence of a boundary at small distances below a wing and its effect increases as the distance between the boundary and wing decreases. The boundary results in the flow around the wing being altered which causes an increase of lift and decrease of drag. This alteration can be considered to be the superposition of two separate effects; chord dominated ground effect (CDGE) and span dominated ground effect (SDGE).

In CDGE the mechanism behind the change in the aerodynamic characteristics of the wing is the change in static pressure on the underside of the wing. This occurs because the total pressure in the flow field around the wing must remain constant. The total pressure is comprised of both dynamic pressure and static pressure and hence the sum of these two components must also remain constant. In the region between the wing and the boundary, the velocity of the air is decreased resulting in a reduction of the dynamic pressure in this region. Hence the decrease in dynamic pressure must result in an equal increase in the static pressure. The increase in static pressure is known as “ram pressure” and is what gives rise to the increase in lift generated by the wing.

While the CDGE increases lift, it is the SDGE which is responsible for a reduction in drag. As mentioned, the total drag is the sum of induced drag and parasitic drag. The parasitic drag results from skin friction and flow separation. However, the induced drag occurs because there is a “leakage” at the wing tips which create vortices that reduce the efficiency of the wing. In SDGE, the vortices are bounded by the ground and hence their strength is limited by the distance of the wings above the ground. Because of this reduction in strength of the vortex, the wing appears to have a higher effective aspect ratio than its geometric aspect ratio. From Prandtl's lifting line theory the induced drag is inversely proportional to the aspect ratio, hence the ground effect results in decreased induced drag.

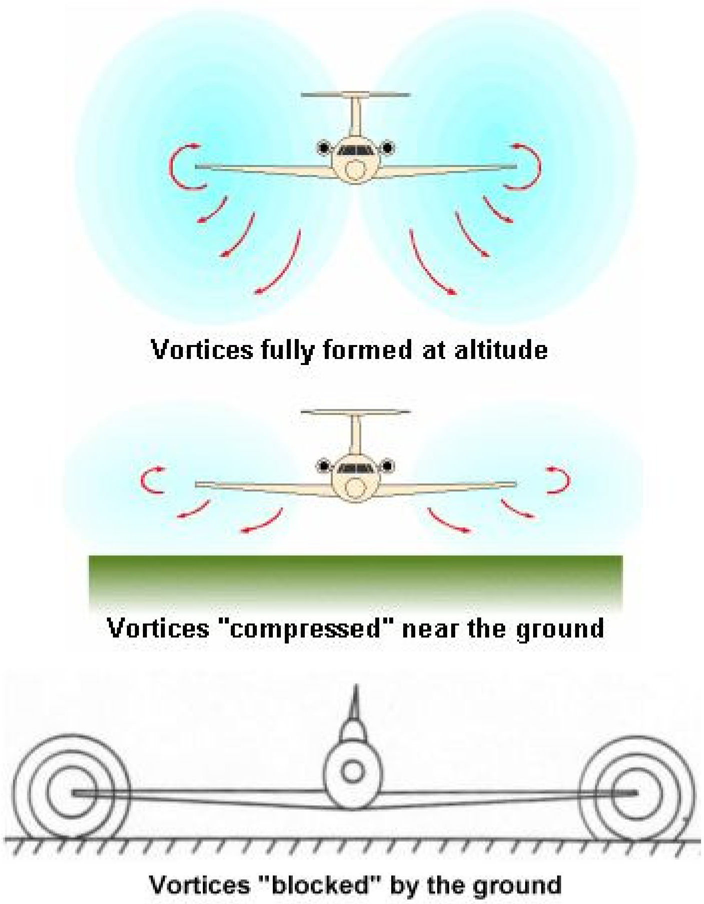

Figure 12:Explanation of vortices created by wingtips [24]

The altered flow field also reduces the downwash angle which results in an increase of the effective angle of incidence at a specified angle of attack. The consequence of this is an anticlockwise rotation of the resultant force vector hence increasing the lift and decreasing the induced drag.

3.3. Pitching Moment

As a wing moves through the air, the pressure distributions on both the upper and lower surfaces create a moment about the aerodynamic centre of the wing. This moment will cause the plane to pitch and hence is called the pitching moment. In order to keep the aircraft stable it is necessary to balance this moment which is generally achieved using additional lifting surfaces such as a canard or tailplane.

In ground effect, the pressure distribution on the lower surface of the wing is altered which results in the aerodynamic centre of the wing changing position. This change of position changes the pitching moment produced by the wing and hence alters the moment which must be balanced in order to keep the WIG craft stable.

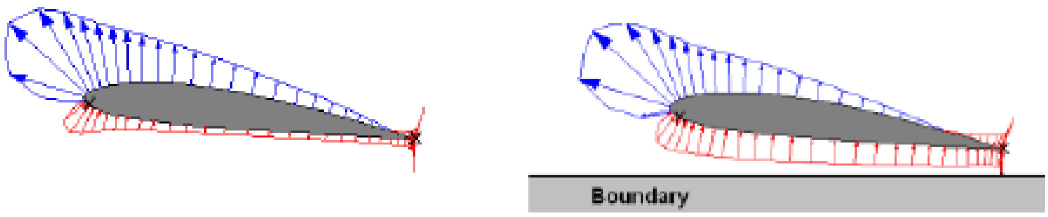

Figure 13: Pressure distribution on Wing [7]

It is a great challenge to design wing in ground effect vehicles because of the stability issue outlined above. The problem becomes more complicated when one considers that the pitching moment changes considerably with height in ground effect. Under extreme ground effect the aerodynamic centre can move as much as one quarter of the chord length from its free stream position.

There has been significant research conducted into designing an aerofoil whose pressure distribution on the underside does not change significantly from in ground effect (IGE) to out of ground effect (OGE). One such design is the S-shaped section which is used on the Amphistar. The drawback with such designs is that they are usually very inefficient in OGE or sometimes even incapable of OGE.

3.4. Maximum Lift

Another important parameter in aerodynamics is the maximum lift coefficient which defines the takeoff and landing speeds as well as the stall speed of the wing. Under ground effect, the maximum lift coefficient can either increase or decrease depending on the aerofoil section and plan form shape. However, It is interesting to observe that an increase in camber of the aerofoil will result in an increase in the maximum lift coefficient OGE however IGE the result reversed. Also IGE, stall occurs at a lower angle of incidence and tends to be more extreme, with lift decreasing more rapidly at stall.

3.5. Effect of Height above the Ground

The effects on an aircraft experiencing ground effect are generally height dependent. This presents a problem when trying to design efficient WIG craft as lift and drag can change significantly with only minor changes in altitude above a boundary. To make matters worse, most of these effects are non-linear which adds to the complication of their design.

In order to predict the behaviour of WIG craft, three separate models are used, each within specified heights of the boundary. Zone 1 is up to a height of 20% the chord length and has a high level of constriction in the vertical direction, with the flow almost approximated as two dimensional. In zone 1 it is CDGE which dominates. Zone 3 is between a height of 1 chord length and 10 wing spans and is dominated by SDGE resulting in a marginal increase in efficiency compared to OGE flight. Between these two regions is zone 2 in which a combination of the two ground effects exists.

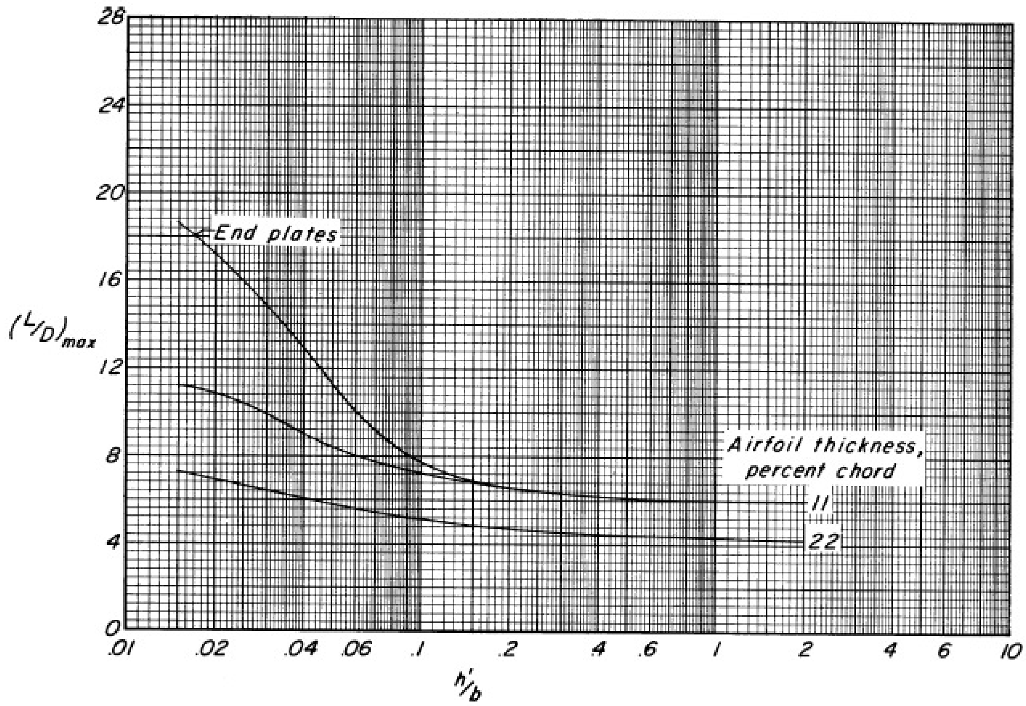

Figure 14: Maximum theoretical efficiency vs. height span ratio [7]

Also it is important to take into consideration the various altitudes which will be achieved during operation of particular WIG craft. Every airborne vehicle whether it be a WIG craft or conventional aircraft will experience ground effect during takeoff and landing however for WIG craft the effect will be more extreme. With WIG craft it is not uncommon for the trailing edge of the wing to be in contact with the boundary surface during takeoff, increasing ram pressure significantly.

During cruise, it is important to maximise the ground effect while maintaining a safe operation altitude above the boundary. This can be difficult to achieve especially if the boundary is the ocean where waves pose a significant threat. In order to perform banked turns, it is required that WIG craft reach higher altitudes and hence leave IGE flight. In these regions the aerodynamics become very similar to conventional aircraft except for the aerofoil which behaves very differently OGE.

3.6. Effect on Different Wing Sections and Wing Planforms

The aerodynamics of aircraft and WIG craft change significantly when different planforms and aerofoils are used in their design. So far the majority of research into the performance of aerofoils in ground effect has been conducted on aircraft sections design for free flight. This has occurred to investigate the effects when aircraft are in close proximity which the ground such as during landing and takeoff.

While most of the research has been conducted on aerofoils which have not been designed to make sustained use of the ground effect, there are a few aerofoils which have been designed to specifically exploit the ground effect. In order to do this the wings must possess the following characteristics; achieve high lift to drag ratios (high efficiency) over a range of altitudes, have good stall characteristics in and out of ground effect and be designed so that the centre of pressure does not change significantly with height.

3.7. Theoretical Benefits of Ground Effect

3.7.1. Efficiency Benefits Compared to Aircraft

In theory it is possible to create WIG craft which have a higher efficiency to aircraft because of the increased lift to drag ratio. They also generally have the benefit of no take off or landing length restrictions which are imposed on aircraft. This means that in theory WIG craft are capable of carrying larger payloads, having a longer loiter endurance or increased range. However, before the theoretical benefits can be fully achieved it is necessary to address three key obstacles preventing WIG craft from doing so.

1. Currently turbo prop and jet engines operate more efficiently at lower air temperatures which are located at higher altitudes. In order to take full advantage of the ground effect it is required that engines be specifically designed for operation at low altitudes. Most current WIG craft use engines not designed for low altitudes and hence sacrifice efficiency.

2. As Wig craft fly in close proximity with the Earth's surface it is required that the hull be reinforced considerably more than conventional aircraft as collisions with waves or other obstacles will be more likely. In order to do this, increased structural weight will mean less payload can be carried and also the hull might not be as aerodynamic increasing drag.

3. In order to balance the pitching (longitudinal) moment, more balancing surfaces such as tail planes or canards must be added. These surfaces also increase the structural weight and drag of the craft.

3.7.2. Comparison to Water Borne Craft

The major advantage which WIG craft have over conventional waterborne craft is the potential for significantly increased travelling speeds. WIG craft are capable of carrying high payloads while travelling at high speeds and are also not very affected by high sea states. In fact high while high sea states may restrict the payload or range capabilities, there is no significant reduction in cruise speed. WIG craft are however limited from taking off or landing depending on the sea conditions which does restrict their operation.

4. Design

A number of compromises are required in achieving an efficient design solution for WIG craft. The best solution will depend on the specifications required for the crafts operation. WIG aircraft have been categorized into three divisions according to their operational purpose. The divisions are:

- Type A: a craft which is certified for operation in ground effect.
- Type B: A craft which is certified to temporarily increase is altitude to a limited height outside the influence of the ground effect but not exceeding 150m above the surface.
- Type C: A craft which is certified for operation outside of the ground effect and exceeding 150m above the surface.

These guidelines emphasize the significant design differences between the different WIG craft types. Type A are incapable of flying out of the ground effect, they require a simpler design solution as they as they do not need to deal with the problem of variable stability. [7, 22]

Type B and C require more advanced design solutions to deal with the problem. Type B is limited as it can only perform leaps to altitude compared to type C which can remain out of the ground effect. Type C operates in free air when out of the ground effect when in this mode the control and aerodynamics are the same as an aircraft. The main difference between these two types is the power. The power of type B is reduced which limits it to only short leaps out of the ground effect.

WIG craft that are capable of out of ground effect operation have no specific operational height limitation and have the advantage of being able to operate in heavier weather conditions. However, out of ground effect operation is particularly inefficient. WIG craft also have the added advantage of operating near the earth’s surface providing low radar detectability. [7, 22]

4.1. Manoeuvrability and Control

The manoeuvrability of WIG craft operating in the ground effect at high and low speeds is extremely inefficient. WIG craft are limited at high speeds due to the fact that they cannot bank turn. As a result they must perform skidding turns. However these turns are undesirable as they are uncomfortable for personnel in the craft and require a very high turn radius. Another option is for the craft to climb to altitude at times out of the ground effect to avoid contact with the surface as it turns. WIG craft generally try to avoid contact with the water during cruise as contact at high speed can cause high structural loads.

WIG craft are required to manoeuvre at low speeds in harbours and ports. The harbour manoeuvrability poses restrictions on wing span and noise emission. Wing span restrictions may limit the size of WIG craft that are able to operate from a particular harbour or port and may also restrict the closeness to shore in which the craft may take off. The engine noise even at slow speeds may well exceed that of conventional marine engines. One possible efficient solution is the development of retractable jets that have the potential to lower the operational noise during low speed manoeuvres. [7, 22]

4.2. Wing

The wing design of WIG craft is defined by the planform and the cross sectional shape. Each of these parameters greatly affects the aerodynamic behaviour and performance of the craft.

The most common planform shape configurations are delta, rectangular, tandem and ram wing. The delta wing was researched by German physicist Alexander Lippisch because of its wing shape that allows stable flight in ground effect. The advantage of the delta wing is it is self stabilising and is the main form of type B ground effect craft. There are two types of tandem wings a bi plane style and a canard style. The canard style design improves the take off efficiency as it creates an air cushion to lift the craft above the water at lower speed, thereby reducing water drag, which is the crafts biggest problem. [33]

The planform shape depends on the desired manoeuvrability and speed of the craft. Flight manoeuvrability is governed by the span length. A large span requires the aircraft to attain a higher altitude before making a turn to avoid contact with the water. The efficient height range for ground effect flight is largely dependent on the chord of the wing. A WIG craft design should have a relatively long chord length, and in order to maintain the surface area they require a low aspect ratio. The aspect ratio of WIG craft are typically in the order of 1 to 3 whereas normal aircraft have aspect ratios of the order of 5 to 10. A better height range is achieved with a higher aspect ratio this however is a trade off for manoeuvrability. A wing operating in ground effect creates a greater pitching moment than a wing operating in the free stream therefore the design of the wing should aim to decrease the pitching moment.

There has been little research into the optimisation of cross sectional shapes specifically for ground effect flight, however one wing shape that has been designed for ground effect operation is the ‘S’ section. Its name describes the shape of the camber line of the wing section and intends on reducing the large pitching moment generated. However such optimised sections have a detrimental effect during out of ground effect flight. [7]

4.3. Tail Plane

A large tail plane is typically used to overcome the large pitching moment generated by the wing when flying in ground effect. The addition of a tailplane to maintain stability and control adds further drag and structural weight to the craft which decreases the overall efficiency. The larger the tailplane and further from the main body of the craft the greater the inefficiency.

The designers of the Ekranoplane decided to make the tailplane 50% of the area of the wing and position it outside of the ground effects. The advantage of this was that the aerodynamic characteristics did not alter with the height of the aircraft. However this design was extremely inefficient. [7]

Figure 15: The Ekranoplane [33]

4.4. Take off

Aircraft operating from water require much more thrust than those operating from land. WIG Aircraft must overcome the drag of the water during take off, which requires a considerable amount of thrust which can not be utilised in cruise. The added drag leads to a greater time taken to reach take off speed and thus the take off distance is greater than normal aircraft. To reduce the amount of thrust required during take off and improve the overall take off performance, WIG craft could utilize hydrofoils and partial hovercraft technology. However the most common method has been power augmentation ram effect or PAR. PAR overcomes the large hydrodynamic drag during the initial take off phase and has shown to increase the total lift by 20% and reductions in take off distance. Using flaps or other aerodynamic devices are a possible solution to increase the maximum lift of the wing, which would also allow the craft to take off at a lower speed and have a smaller take off distance. [22]

4.5. Landing

The structural loads experienced during landing are not as critical as those during take off. However the impact loads experienced by the hull can be reduced by the development of hydrofoils. A hydrofoil is intended to slow the craft at a decreased rate as it enters the water, thus reducing hull loads and providing a safer landing.

4.6. Engine

The operational performance is the major factor to be considered in the selection and placement of the engine. The takeoff phase requires the most thrust than any other phase of WIG craft. Hence this governs the placement, size and quantity of the engines. The type of engine used is determined by the amount of thrust required for take off and the desired operational speed. The most common engines that have been utilised in WIG craft are the piston, turbo prop and jet engines. The Piston engine is used for low speed, low power and low altitude whereas the turbo prop engine is used for higher power requirements at moderate speeds. If high speeds are required for operation the jet engine is most efficient as they have a high thrust to weight ratio.

If PAR technology is to be utilised the engines are mounted in front of the leading edge of the wing. This allows part of the slip stream from the propeller to flow over the upper surface of the wing, causing a higher upper surface velocity, which creates a larger suction force, increasing the total lift of the wing. The use of PAR technology to reduce the take off load incurs a number of problems in relation to mounting the engines so close to the water surface. The biggest problems being the lack of visibility due to spray, the excess power required for take off that can not be used in cruise and water ingestion into the engines. As a result of water ingestion, corrosion and other performance aspects relating to the engine become more significant. [7, 22]

For all types of engines it is necessary to have some sort of resistance to corrosion from the salt water environment. The salt in the air passes into the compressor of the engine where it collects on the inner surface and blades, this alters the aerodynamic shape of the blades and can cause compressor stall. This results in a loss of power and may cause structural damage to the engine. Research into improving the service life and durability of engines will reduce maintenance and operational costs.

The excess power required for take off that can not be used in cruise has two effects on the performance of the craft during cruise. The engines are forced to operate at an inefficient thrust level in cruise, the engines may even be shut down which causes increased drag due to their windmilling. A possible solution would be to design an engine which could operate efficiently at a lower thrust level in cruise and still be capable of generating a high level of thrust for a short period of time which is required at take off.

4.7. Fuselage

The design of the fuselage is governed by the intended operation of the craft. As the craft flies at low altitude the fuselage is not required to be pressurised so designers are not restricted to a circular cross section shaped fuselage. The aircraft can be designed to hold large cargo which would dictate the shape of the fuselage which would not normally fit into a pressurised transport aircraft. The hull shape should be designed to minimise the drag through the water and hence the time taken to reach take off is reduced and increases the low speed performance of the aircraft.

The ability to deploy and retrieve objects and personnel whilst drifting is possible depending on the size of the craft and the design of the fuselage. Small WIG craft could operate from the deck of ships, being lifted into the water. Another consideration is to reduce the magnitude and frequency of forces experienced by personnel in the hull of the aircraft. To reduce the magnitude stabilisers and dampers could be included in the hull design. [7]

4.8. Amphibious Performance

WIG craft may be designed for amphibious operation the given advantage being able to load and unload from beaches and operate from airstrips. However such a design carriers heavy weight penalties as it will require additional structural strength which increases the inefficiency of the aircraft. A take off aid would be required for an amphibious aircraft to lift the craft from the beach. Possibilities for amphibious aids are providing the WIG craft with hovercraft ability, air cushion skirts, sleds and skis. The Orlyonok was able to transfer itself from the sea to land by using wheels in its hull. [7]

Figure 16: Two Orlyonok on a platform [7]

4.9. Transport Efficiency

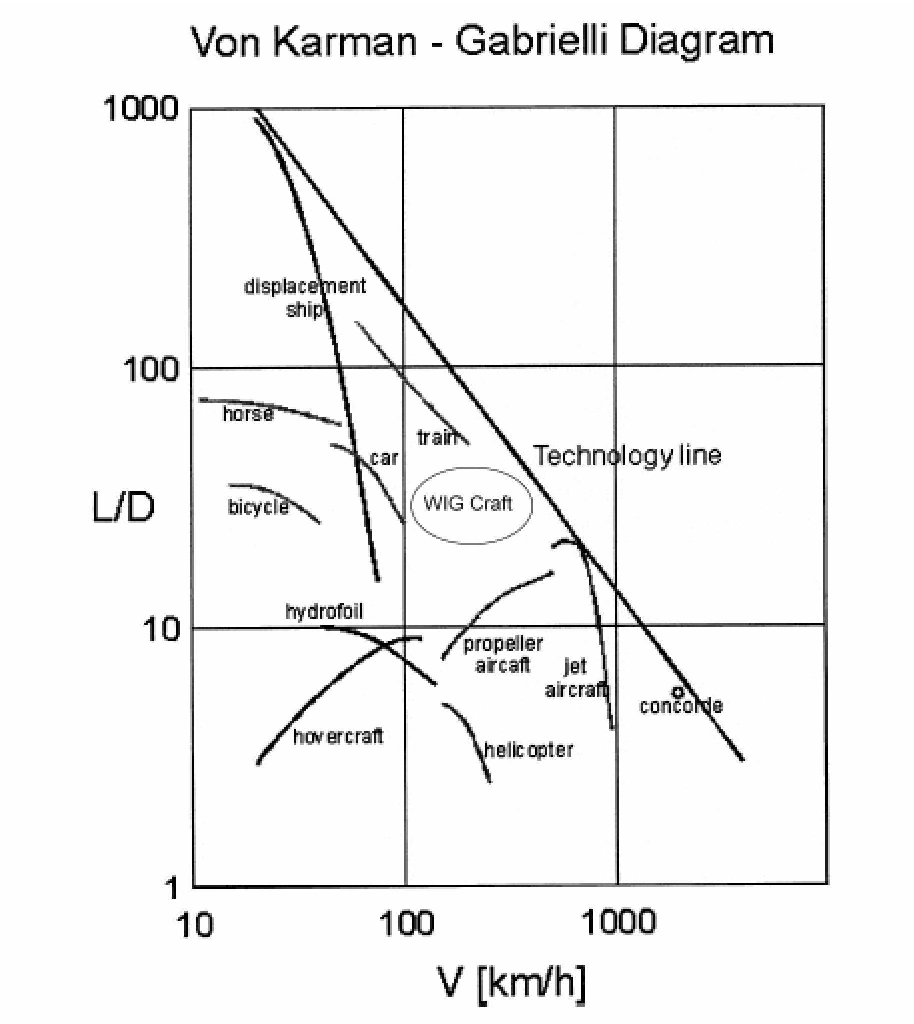

Figure 17: Transport Efficiency [30]

Von Karman - Gabrielli diagram shown in *Figure 17* shows the efficiency of a transport medium. The 'Technology Line' represents the current ability to achieve a certain speed with a desired payload at a minimum power.

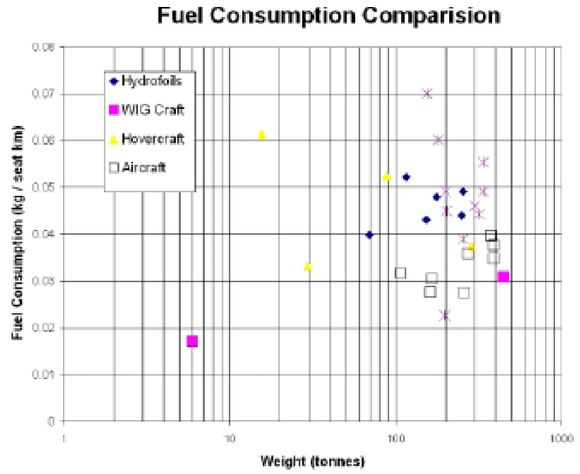

Figure 18: Fuel Consumption [20]

The fuel consumption comparison for a craft is a useful measurement to show the efficiency of a craft. Most of the craft with a higher value of weight with proportional a higher value of fuel consumption. But *Figure 18* shows that the fuel consumption of a WIG craft has acceptable fuel consumption rate with respect to the weight.

4.10. Range and Payload

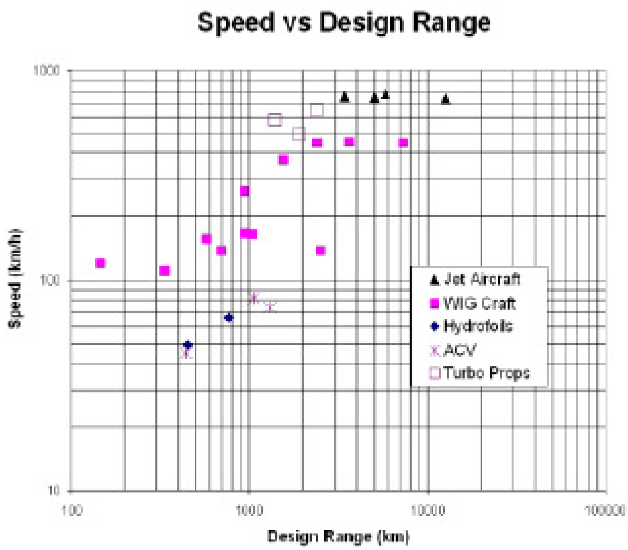

Figure 19: Range and Speed of WIG craft [21]

In *Figure 19* show that the WIG craft have the potential to fill the gap in between the aircraft and ships. The jet aircraft have the highest speed than other and with a higher range. Many of the WIG craft have a lower range than high-speed Jet Aircraft. Only two of the WIG craft approach the achievable performance of jet aircraft.

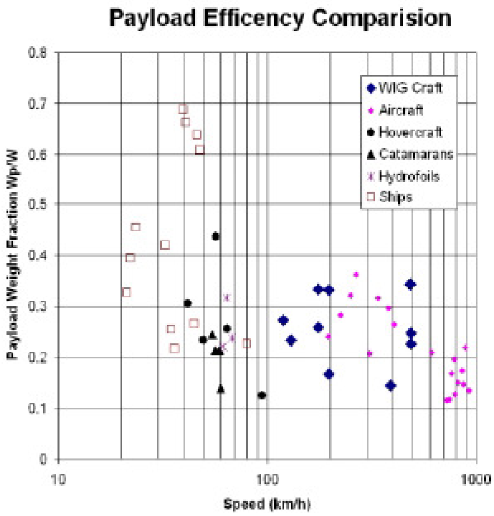

Figure 20: Payload Fraction versus Speed [20]

In *Figure 20* show a measurement of the structural efficiency of a craft. The Payload Weight (W_p) fraction of the total weight (W) for aircraft is lower than the ships so the speed for aircraft is higher. Existing WIG craft provide similar or slightly lower payload weight fractions than aircraft while operating at a lower speed.

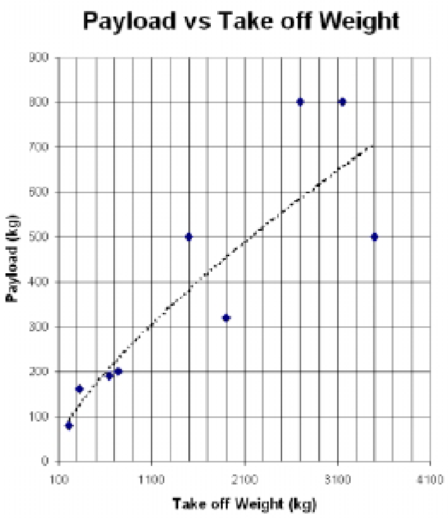

Figure 21: Payload for Various Size WIG Craft. [25]

In the *Figure 21* showing the comparison of payload weight against take off weight for existing WIG craft is presented in. The tendency for the fitted curve to show demonstrate of the smaller structural efficiency of the smaller craft so far constructed.

4.11. Sea State

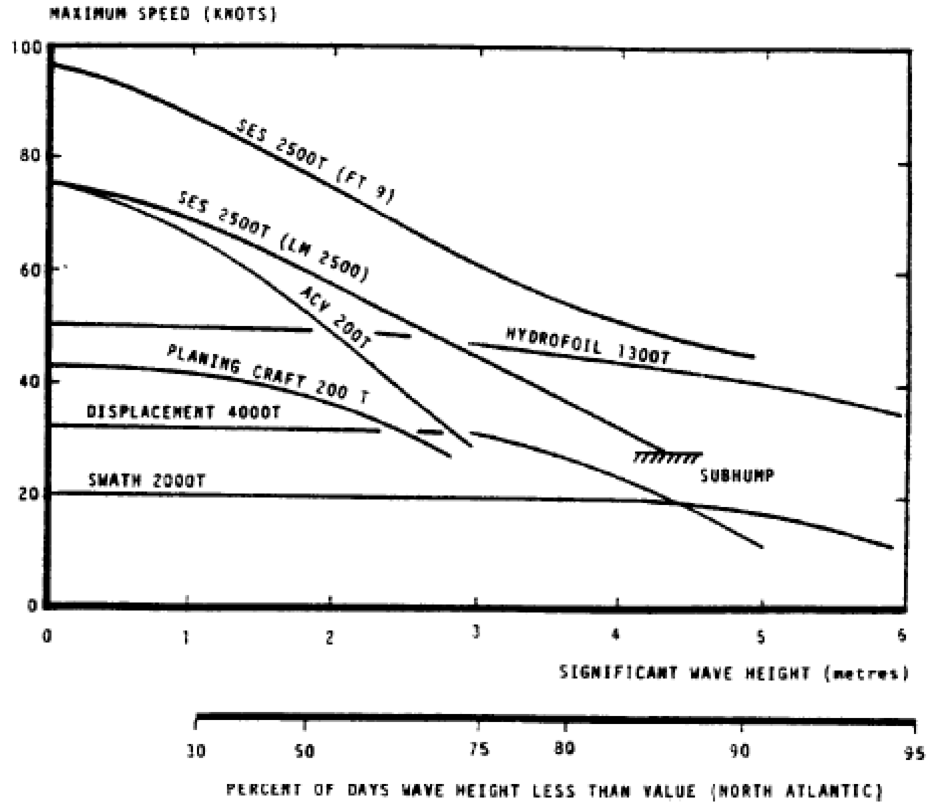

Figure 22: Wave State and Sea Craft [17].

WIG craft have to fly at a higher altitude to avoid the contact with waves. Vice versa as the craft flies higher it loses the benefits of ground effect. Conventional craft's speed is affected by sea state operation and this is demonstrated in *Figure 22*.

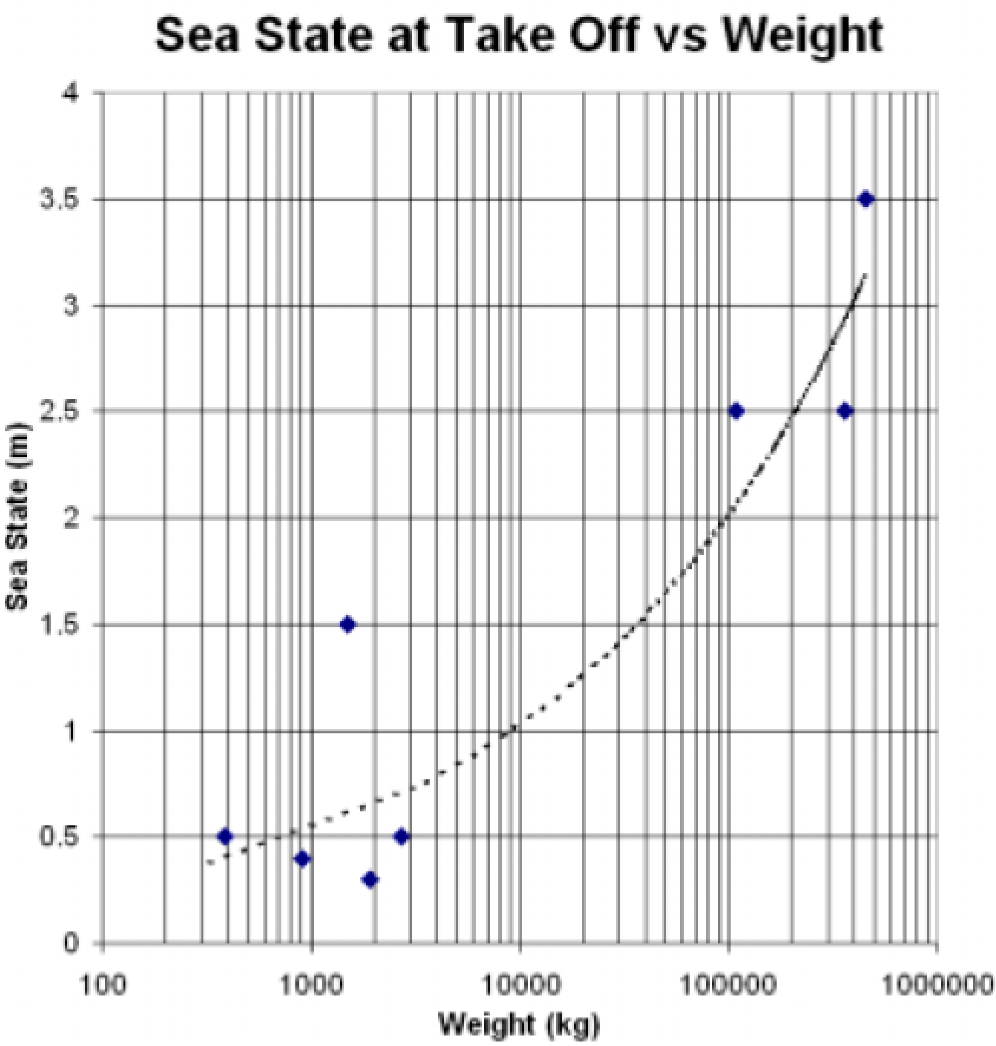

Figure 23: Sea State at Take off for various WIG Craft [25]

In *Figure 23* show the Sea State take off for various WIG craft, the lower weight can attempt the lower Sea State. From the *Figure* 23 the heaviest WIG craft can reach 450000kg with 3.5m Sea State.

4.12. Cruise Performance

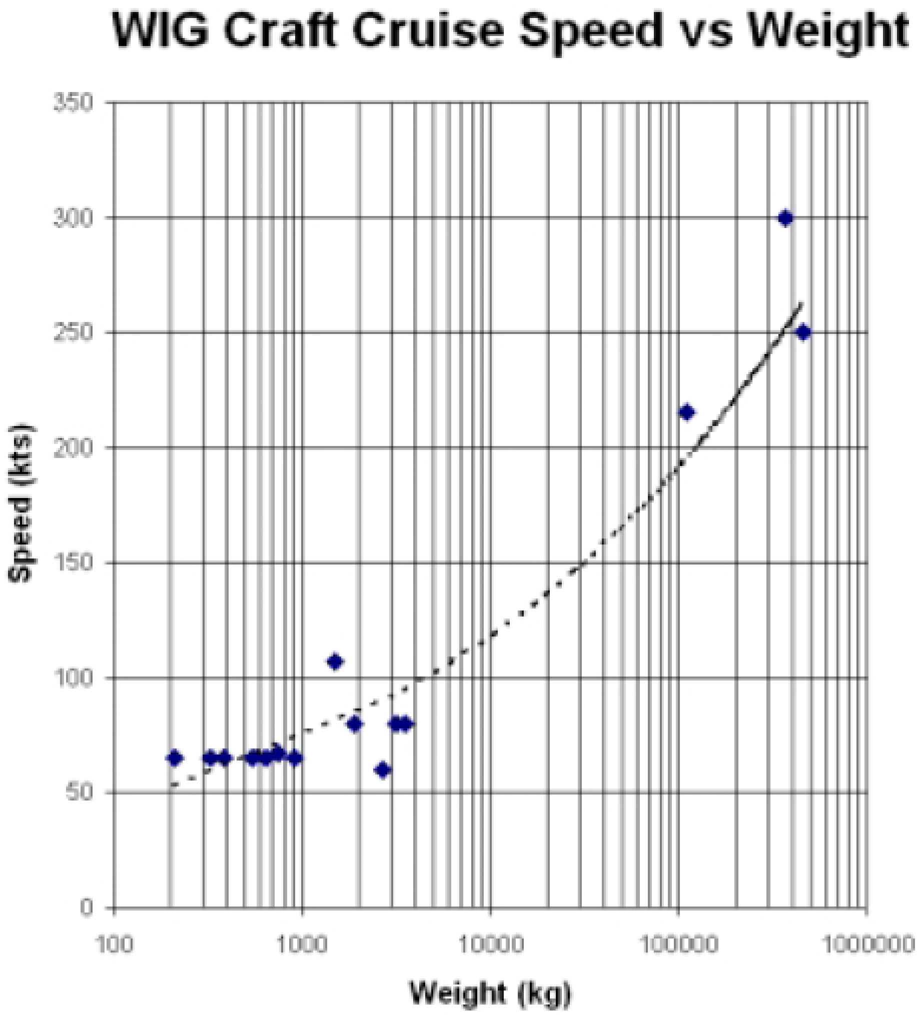

Figure 24: Cruise Speed versus WIG Craft Weight. [25]

Effectively the thrust available and the drag of the craft determine the cruise speed of a WIG craft. However, efficiencies of scale tend to mean that craft with high thrust are also relatively large. In *Figure 24* show the WIG craft cruise speed and maximum weight. There is a large collection of craft under 5,000 kg and the three large USSR craft between 100,000 and 400,000 kg. Common WIG craft is below 5000kg.

4.13. Take off

WIG craft have similar hydrodynamic drag with seaplanes. Hydrodynamic drag for WIG craft can be broken down into the following categories such as the hull of the WIG craft, the wings in contact with the water, the spray of the hull and the engines and the hydrodynamic drag of the endplates.

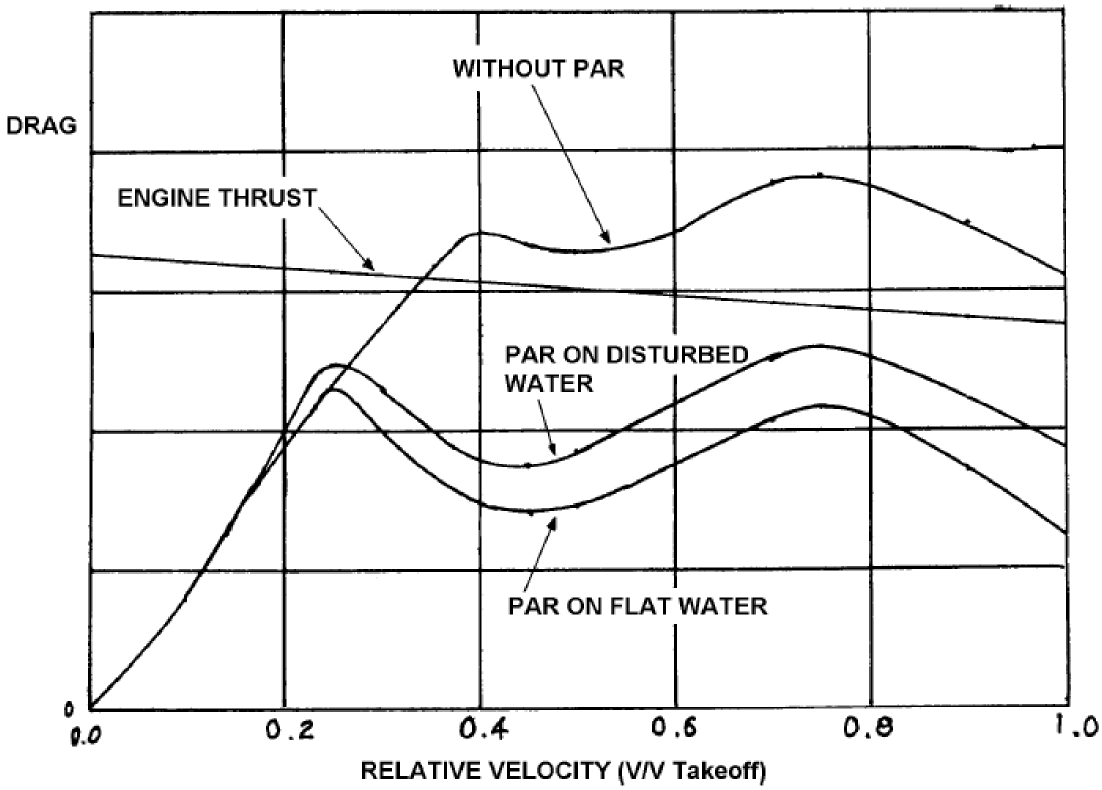

Figure 25: Velocity versus Drag during Take off [15]

Figure 25 displays a graph as the aircraft is taking off. The four different alternatives are shown in this graph. These are low speed displacement, hump speed, planning, speed and take off speed.

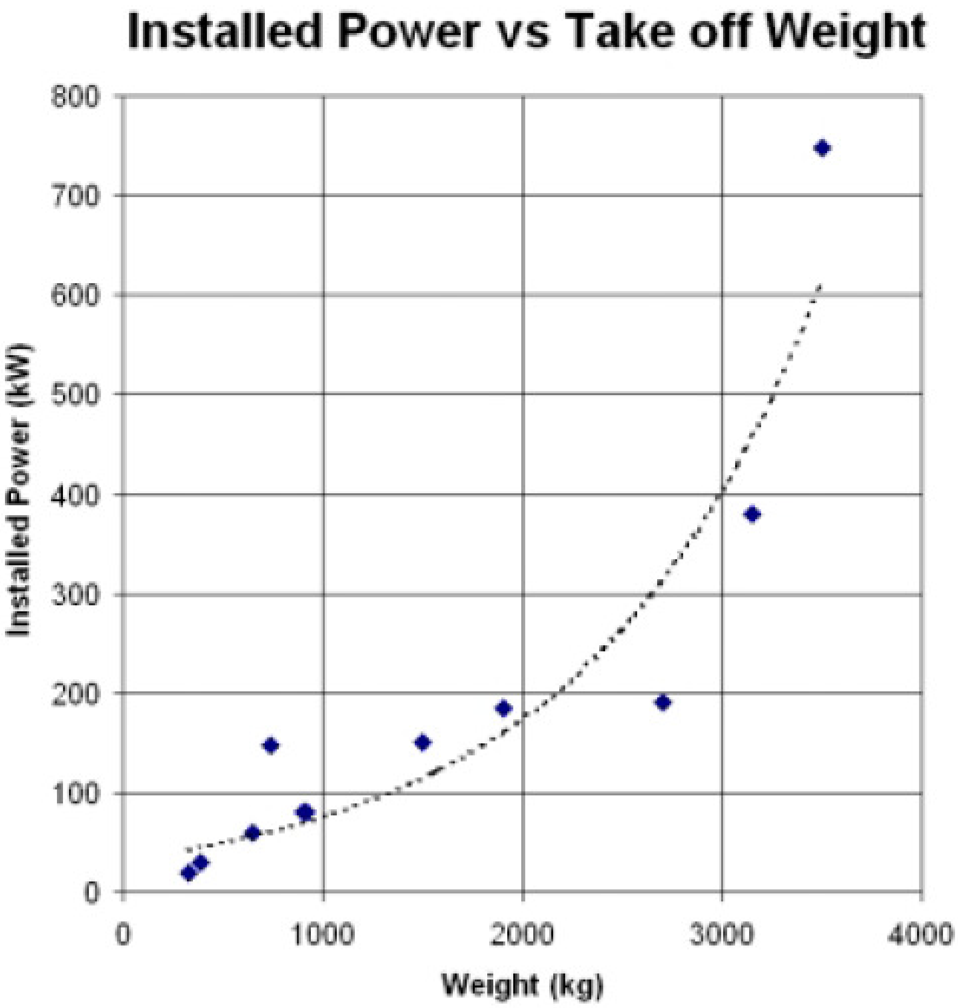

Figure 26: Installed Power for Various WIG Craft [15]

In *Figure 26* show the power required for take off of the WIG craft. As commonsense the more heavy craft required more power to take-off. As the take off is the most critical power requirement in all WIG craft configurations currently tested, any reduction in the take off power will lead to performance, weight, efficiency and cost benefits.

5. Benefits and Advantages of the WIG Effect

Most aircraft are able to benefit from the wing in ground effect. As a plane comes in to land, the cushion of air formed as a result of the ground effect allows for a softer landing.

The primary benefits of the wing in ground effect come from the additional lift provided by this phenomenon. This lift allows the craft to remain airborne with less power required from the engine. This improves craft fuel efficiency and allows it to fly further and with a greater payload. This increased fuel and energy efficiency also makes a craft more environmentally friendly and less noisy [32]. The close proximity of the craft with the ground also reduces lift induced drag. These benefits provide enormous potential for WIG craft to be used for high speed cargo transport. WIG craft could potentially do the job of a ship, only much faster since they don't experience water drag to the extent that ships do [7].

With regard to safety, should a WIG craft experience an engine failure and crash, damage is likely to be minimal as the craft will not have far to fall, particularly if the craft falls on to water. Furthermore, if the water is relatively calm, a WIG craft could land at any time. For recreational purposes, some small craft could be operated by civilians with a boat licence, rather than a pilot's licence [33].

Helicopters may also benefit from the wing in ground effect provided that the ground is a hard surfacer, as less power is required to hover close to the ground as opposed to hovering out of the ground effect. A helicopter that is experiencing engine failure may still be able to hover in the ground effect when it would be otherwise impossible [8].

6. Dangers and Disadvantages of the WIG Effect

While the wing in ground effect is, for the most part, beneficial to aircraft, it does pose some dangers to regular aircraft and provides limitations to the design of WIG craft. With regard to regular aircraft, the potential dangers of the wing in ground effect come into play more so during landing, rather than take off. Craft flying in ground effect are generally longitudinally unstable (unstable in pitch). As a plane comes in to land, the additional lift can cause an undesirable change the angle of attack of the wings of the craft. In the hands of a relatively experienced pilot, this is generally simple to control but if not properly corrected, this effect could eventually lead to stall, since the craft is rising and decelerating [14]. The sudden loss of lift from stall can in turn result in a ‘pancake landing’, where the plane falls flat onto the ground, which would damage the plane and possibly harm the people inside. Furthermore, when landing at fast approach speeds, the ground effect could cause the plane to float and overshoot, missing its desired landing spot [8].

One potential example of a ground effect hazard for helicopters could be on an aircraft carrier. The ground effect provides the lift for the helicopter to lift off, but if it gets to the end of the carrier runway without sufficient speed, the ground effect lift will disappear and the helicopter will fall toward the sea [16]. Other potential hazards exist for helicopters that are hovering above a solid reflective surface such as concrete. If there is a lot of heat present under the craft, that heat may be reflected from the ground back up to the craft causing damage to the structure and other components.

The vast majority of WIG craft have been designed to fly over water. This alone presents several potential problems. The first of these problems is corrosion. The craft will suffer extensive corrosive damage, particularly on load bearing structures, when flying close to sea level if its material is not sufficiently corrosion resistant. Another problem of flying close to sea is having exposed mechanical components of an aircraft, such as propellers. Some of these components can be relatively fragile and vulnerable to water spray from the sea. This can lead to further aircraft damage. These factors result in the craft having a reduced reliability and greater perceived risk. Furthermore, craft vulnerable to sea water will require extensive maintenance, which will add to their life cycle cost. The cost may become unfeasible for the craft to continue operation. Another problem with near sea level flight is water drag, which can provide additional drag to the craft, thereby reducing its efficiency. Water drag becomes a problem particularly if the WIG craft is trying to fly out of ground effect. The extra power required to overcome this drag greatly requires large, heavy jet engines resulting in increased fuel consumption [1]. This combined with the low aspect ratio of the wings, reduces the crafts efficiency and counteracts the primary benefit of wing in ground effect flight, which is less power needed to sustain level flight.

Sea state, which refers to the roughness of the seas, obviously affects the altitude at which a craft can fly. If the seas are too rough and unpredictable, the craft will not be able to fly safely over that water in ground effect. A craft could react to a change in sea state by increasing altitude, but once again, the increased power needed to ascend would decrease the fuel efficiency of the craft. Yet another problem with WIG craft is that take off must be into the wind, meaning that a launch over water requires flying into the waves. The power augmentation (take off aid) solution implemented in the Soviet Ekranoplans further reduced their fuel efficiency [33].

With regard to initial cost, WIG craft are generally more expensive than the boats that they are intended to replace, although they can be cheaper than seaplanes and helicopters with equivalent capabilities. The costs of a WIG craft are often increased as more cutting edge technology is implemented into the craft [32].

Other design compromises have affected the effectiveness of previous WIG craft. The craft have required a strengthened hull structure, which adds to the overall cost and weight of the craft. Another requirement is for the craft to feature a reduced wing aspect ratio since the ground effect already provides additional lift. However, low aspect ratios result in greater drag and poor gliding [7].

The aforementioned longitudinal (pitch) instability also applies to WIG craft, which, combined with the reduced aspect ratio, can make the craft quite difficult to control and thus require more additional control forces and computer assistance when compared to a traditional aircraft. Despite this extra assistance, many WIG craft have crashed in the past due to pilot error, further illustrating the difficulty of WIG craft control [33].

7. Applications and Operations using the WIG effect

Throughout the world today, there are very few commercial aircraft that use the WIG effect. This is because there is still much research and development needed in the feasibility of these aircraft. In fact, there are currently no WIG aircraft that are in current use for any Navy worldwide. The fact that the WIG effect occurs at a very low altitude means that the terrain on which WIG aircraft can fly over must be very flat with no sudden changes in surface gradient. This is why the main use and operation for the WIG aircraft is over seas, lakes and oceans, where terrain does not vary. In addition, since the aircraft travels at very low altitudes this can be a benefit for stealth-type aircraft. Thus the two main applications of WIG aircraft are identified as being stealth and water-faring airplanes.

There are three main types of WIG air vehicles. Class A is the first type which means that the aircraft is only capable of low altitude WIG flight. It is thus unable to fly out of ground, as in it cannot function in higher air. This type of aircraft could only ever fly over water. Class B represents a WIG aircraft that can leap over reasonably sized land masses and obstacles and can reach a height of up to 100m. The last class is Class C which can achieve flight in higher altitudes for longer periods. [7]

An important use and application of a WIG aircraft is as a large transport aircraft. As shown earlier the wing in ground effect provides an excellent lift to drag ratio, which means that when in cruise a WIG aircraft can potentially be much more efficient that a conventional Out of Ground (OGE) aircraft. For this reason, potential WIG aircraft can be made into larger aircraft that are much more efficient. A novel idea that is undergoing development and feasibility studies is the ‘wingship’. It has such a name because it is a cross between a air-faring vehicle and a sea-faring ship. Its main potential advantages are that it fly a lot faster than a conventional sea faring ship and it is much larger than any air-faring vehicle. This means that its main use is as a transport ship for either commercial or military purposes. The Soviet Union developed a large craft commonly known as the “Caspian Sea Monster” in the US. It was nicknamed the “Caspian Sea monster" because of how large it was and how it was unknown as to what it fully was by the Americans. A more in depth look at this large 'wingship' will follow. Advanced research by the Soviet Union has shown it is possible to build such a 'wingship' that is much larger than an OGE air-vehicle and much faster than a ship. This ship has since then sunk and the Russian navy have since ventured to develop large WIG aircraft called the Orlyonok and Lun, which are not as large as the 'Caspian Sea Monster' but the Lun is still larger than a Boeing-747. In the United States, the feasibility of such a large transport 'wingship' is being tested. A fairly recent design called the Aerocon is under proposal and its size would be much larger than any known aircraft in history. If developed, it would be around 5000 tonnes (1500 ton payload and can support of 2000 troops). The following diagram shows the size comparison of such a large scale 'wingship.'

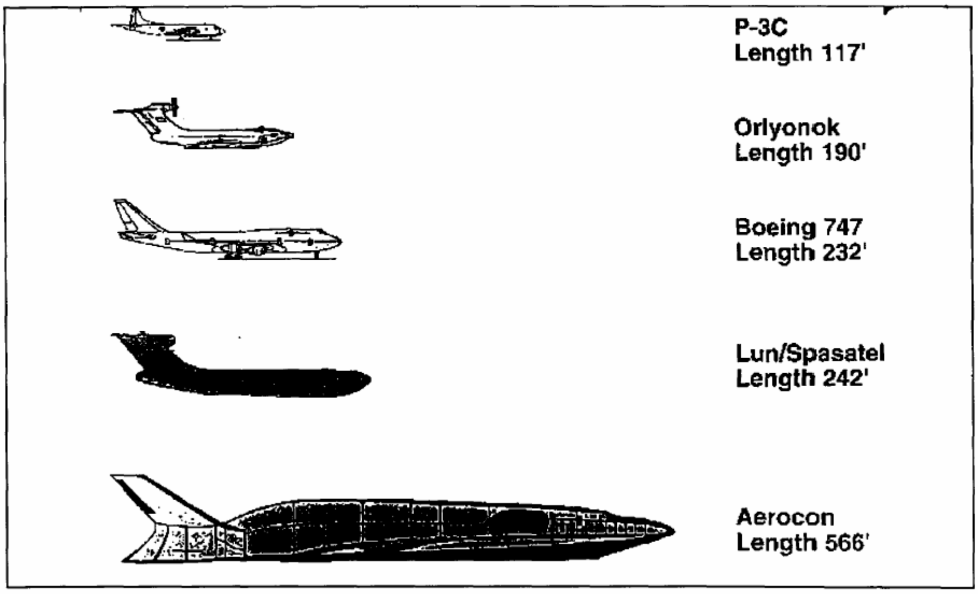

Figure 27: Comparison of different WIG craft and aircraft [7]

The main downside to the production of the Aerocon is the cost involved because of its innovation and also the large scale power required to raise the craft above the water so that the wing-in-ground effect can take place. The Ekranoplane ('Caspian Sea Monster') has shown that such a large WIG craft can be build, however whether it is the most efficient and effective means of large scale transport is an area which is still to be explored.[13]

Another important application of a WIG airplane is as a sea and rescue craft. Since these craft continuously fly low to the ground, can land in the sea and can travel faster than a regular helicopter. They are thus an excellent option as a rescue craft. An example of such an aircraft is the Russian Rescue design called the “Spasatel”. It is an ideal sea and rescue airplane since it can arrive at a rescue scene much faster than a helicopter. Its cruise speed at low altitudes is between 400-550 km/h and up to 750 km/h at OGE altitudes. It can also conduct its rescue missions in rough weather conditions with waves of up to around 3.5 to 4 metres high. This aircraft is also very large and would be suitable for large scale rescue missions, for example when a commercial passenger ship or aircraft has crashed. Much like the large transport WIG aircraft, the Spasatel can hold up to 500 people, which is much more than any OGE rescue aircraft or helicopter. Due to the size of such WIG aircraft, these can also hold large amounts of medical equipment. This can be very beneficial in rescue missions and can help save lives.[22]

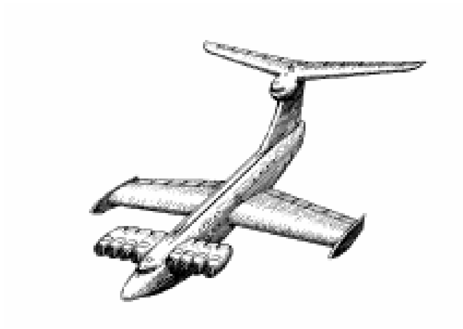

Figure 28: Search and rescue Ekranoplan “Spasatel” [22]

There are many other civil applications for WIG craft. WIG craft can potential be used as surveying aircraft for geophysicists, because they can cover a large area of land or sea at low altitudes. In addition, they could be used as fishing vessels, coastal guard operations or even in courier/delivery applications over seas and oceans. Small WIG aircraft can be used similarly to light aircraft as commuter craft and light transport. The Wingship aircraft like the Aerocon could potentially be used in many different applications. Commercial transport of large numbers of people, major search and rescue operations and transport of goods are all possible civil applications of such large WIG craft.[22][2]

There are quite a few naval applications of WIG aircraft that have much potential now and in the future. Due to the fact that WIG craft are fairly fast and fly very low means that they are not easily visible especially on radar and are ideal for stealth type craft. As an attack aircraft for naval purposes, WIG aircraft are potentially quite effective. Since many WIG craft are quite large with large payload capacities, they can possess large quantities of weapons. Two main applications of attack WIG craft is as an anti-surface craft or as an anti-submarine craft. An example of an anti-surface craft is one developed in 1966 called the Grumman. The closeness to the water surface meant that it was less visible and much faster than the naval warships. Boeing have previously developed an antisubmarine craft named the “lowboy”, which has the ability to store and deploy many weapons and protection systems, such as torpedoes, sonobuoys and mines. [22]

Amphibious craft is another type of WIG craft in application. An amphibious aircraft is one that can land either in water or on the land. This means that such a craft would have to be of type B or type C, since it must be capable of flying over different terrain. The Russian “Orlyonok” is an example of such a craft that has been developed as an Amphibious craft. In addition to these amphibious craft, other Naval applications of WIG aircraft include Sea Lift which is much like what the large Wingship style aircraft are design for. These craft could also possibly be used for Nuclear launches or as missile launch craft or as Reconnaissance and Patrol style missions. The low altitude of the aircraft however does not aid in Reconnaissance as the total visible area is reduced. [22]

There are many possible applications for WIG aircraft in both a civil and military sense. There are many potential projects such as the Aerocon that are under development. Although there are many applications, WIG aircraft are yet to become in more use. Through more research and development into the efficiency and effectiveness of such aircraft, the applications of such aircraft will be more sought after.

8. CASE STUDY: The Caspian Sea Monster

In 1967, the US Defence Intelligence Agency noticed from satellite imagery a very large and unusual craft. At the time, they named it colloquially as the “Caspian Sea Monster” due to its very large size. At the time it was regarded as the largest aeroplane in the world. Today it still remains as the longest aeroplane ever built. An analysis of this craft and its design will be done and comparing it with other large well-known OGE aircraft.

The “Caspian Sea Monster” is formally has the ship model name Korabl’ Maket (KM). It was developed as an experimental Ekranoplane and as a final product did not serve a true practical purpose other than verifying that a large scale WIG aircraft can be built and operate successfully. It was first designed by reknowned pioneer in WIG aircraft, Rostislav Alexeyev. The first model of the KM craft was constructed in 1965 and its first flight was undertaken in 1966. During the period of operation there were a total of 8 KM WIG aircraft built, each with modifications and variations upon the previous model and the last KM craft was produced in 1978. In 1969, one of the KM aircraft crashed as a result of foggy conditions and pilot error. Again in 1980, the “Caspian Sea Monster” crashed and is thought to be due to pilot error. Supposedly, the pilot did not set the engines to full throttle and the Ekranoplane then crashed due to not enough lift. These aircraft wer then attempted to be recovered, however due to its massive size the aircraft have yet to be uncovered from the sea floor.[10][19]

Figure 29: The Caspian Sea Monster drifting [31]

Throughout the whole time period of production of the KM, the wingspan varied between 32 and 40 m and the length between 92 and 106 m long. The maximum height of the KM was 22m from the undercarriage to the top of the tail wing. The KM was designed specifically as a class A type WIG craft and only ever travelled over sea. The construction of the KM was primarily using stressed Aluminium with a titanium-coated skin. The “Caspian Sea Monster” was designed using 10 Dobryin VD-7 turbojets, eight of which were located at the front of the craft and 2 located on the tail of the craft. The two on the tail were for providing extra thrust at the start in order to bring the KM above the surface and out of the water. These two rear engines each have spray deflectors to reduce water entering the engines, whilst the high and frontal position of the front eight engines means there is much less sea spray entering these engines. Each VD-7 turbojet engine can generate thrust of just over 100 kN. These engines could propel the craft at a maximum speed of 500 km/h, with a maximum range of 3000 kilometres. [10][28]

Figure 30: The Caspian Sea Monster in cruise [31]

It can be seen from this picture than when in cruise, the KM airplane travels at a very low altitude to incorporate the WIG effect. The trails of water from the two wing tips can be explained by the trailing vortices created on the wing tip which force some spray outward from beneath. The induced drag caused by the wing tips is shown to create this spray from these edges.

In this comparison, the Caspian Sea Monster is being compared with modern day large aircraft. The Antonov An-225 is the largest ever aircraft built, the Airbus A380F is currently the largest commercial passenger aircraft, whilst the Boeing 747 is the most well known large passenger aircraft in current use. If we compare the mass of the four large planes, it can be seen that the Caspian Sea Monster is significantly larger than the Boeing 747 and at the time of when it was first built, it was twice as large as any other airplane built before it. [29]

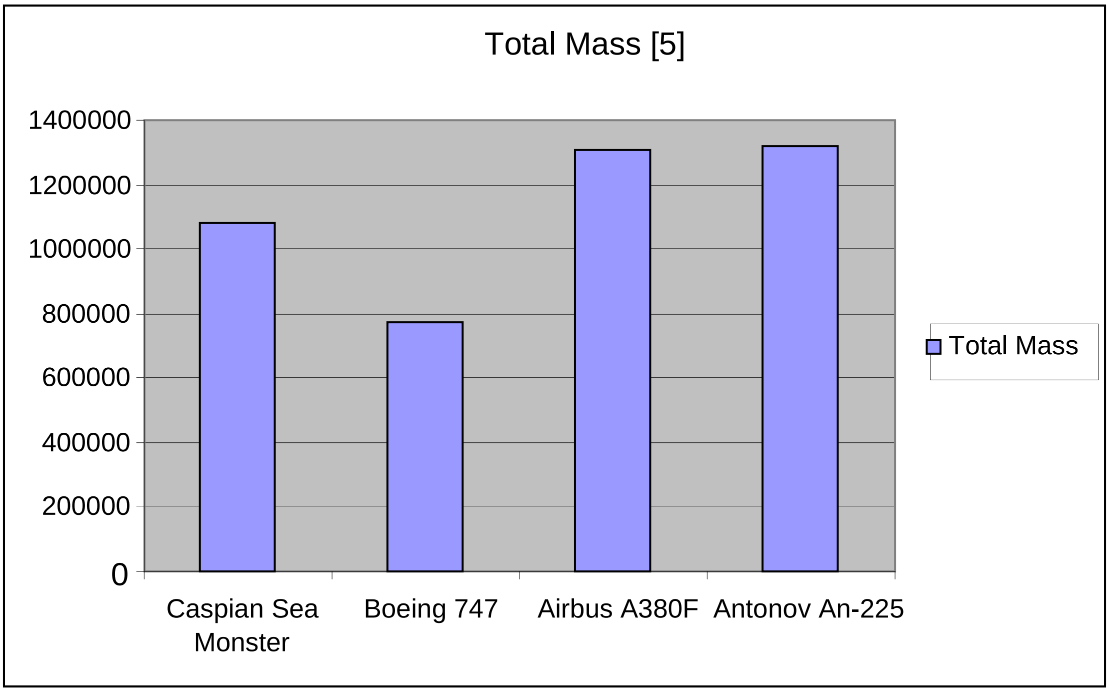

Figure 31: Graph of the Total Mass of different vehicles

If one compares the wingspan and length of the four large aircraft, it can clearly be seen that the length of the KM is significantly longer than the three others, however the wingspan of the KM is significantly shorter. The length of the KM is more than twice its wingspan, however for the other three OGE aircraft their respective wingspans are similar to their length. The reason for this is the design of the KM. Most WIG aircraft are designed with low aspect ratio (stubby-shaped) wings, due to the fact that the Wing-in-Ground effect provides significant lift and so the wingspan does not need to be as great to generate the required lift for cruise. In addition the short wingspan allows the craft to turn more easily and improves its harbour manoeuvrability.

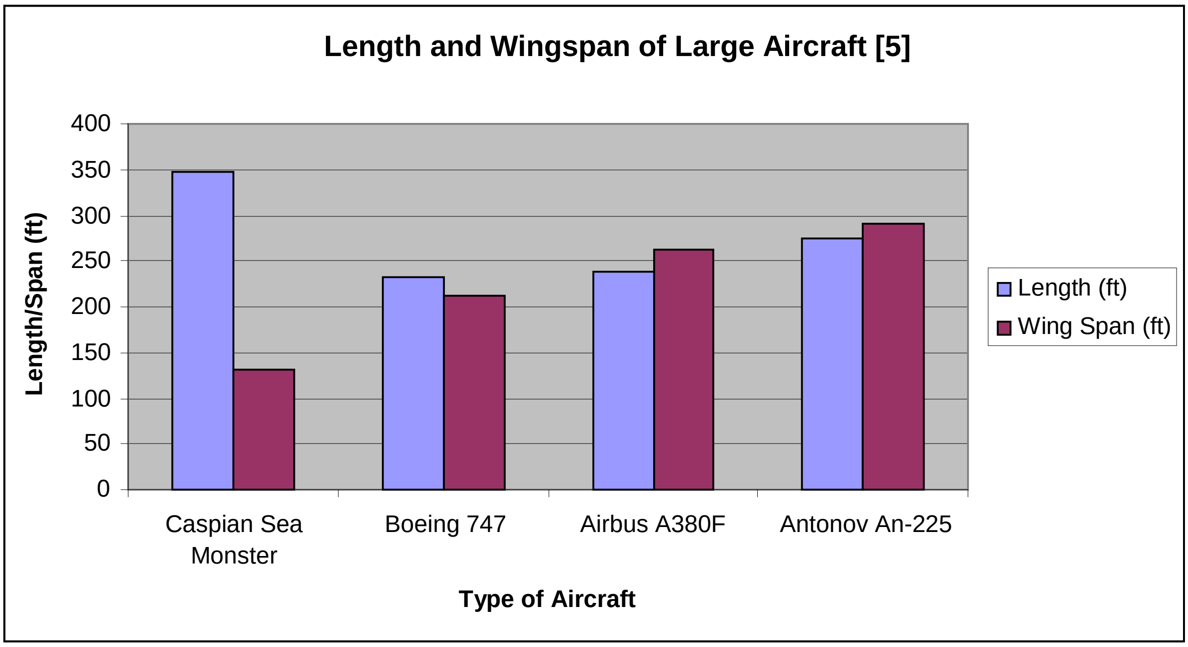

Figure 32: Graph of the Length and Wing Span of different vehicles

The control mechanisms for the KM aeroplane include 8 parts of powered elevators to change pitch in take-off and landing, three air-powered rudders to control yaw and two powered ailerons at the wing tips. Since the airplane uses the wing-in-ground effect it does not use roll as means of turning and so the rudders are used much more and this air vehicle acts more like a sea ship than an aeroplane.

The KM has for long been a mysterious aircraft that has a very unusual appearance unlike any other OGE aircraft. The position of the engines and the shapes of the wings is such that it can operate at low altitudes utilising the wing in ground effect with sea conditions. The materials used like Aluminium and Titanium are such that they are corrosion resistant, especially due to the high speeds and proximity to the water. Its success as a practical transportation or military air vehicle however is questionable, since two out of eight have proved to fail (although pilot error was involve). It is a credit to the Soviet Union in their development of such a large scale WIG aircraft and is an aircraft like no other of its time.

9. Recent Developments

Research and development of WIG effect technology and vehicles is currently very active. Russia, China, Germany, and the USA are currently leading these developments. WIG effect vehicles are being developed for a variety of functions including passenger transportation, cargo ships, and for use as sports craft as well as for military applications. Much research is also being conducted at engineering departments at universities in many countries. The purpose of the following section is to provide a brief survey of some of the recent developments in WIG effect vehicles, as well as proposed future vehicles.

9.1. Projects in China

Research and development of WIG effect vehicles has been carried out by The China Ship Scientific Research Centre (CSSRC), MARIC, as well as the Marine Design and Research Institute of China (Marie). The CSSRC commenced development and design of WIG effect craft in 1967 and since then, China has tested nine manned test vehicles [1,18,11].

Of note is the XTW series, developed by the CSSRC, which are based on a wing-tail configuration with a main wing with forward sweep as in Lippisch designs [22]. Vehicles in the series include the XTW-I, XTW-II, XTW-III, and XTW-IV. The XTW-IV is typical of the series, and is capable of seating 20 passengers [22]. The design comprises of a major hull (float), with the main wing supported by two minor floats and two vertical stabilisers carrying a high-mounted tail plane [22]. Two turboprop engines with 5-blade adjustable pitch propellers are mounted at the leading edge of the main wing [22].

During the early 1980's MARIC started development of what they named AWIG (Amphibious WIG) vehicles. After testing approximately 80 models and a radio controlled model, the AWIG-750 was built. The AWIG-750 has a maximum towing capacity of 745kg [22]. The craft is powered by four internal combustion engines, two being used to generate lift with the remaining two used for propulsion [22].

The craft has a maximum speed of 165km/h [22]. The wave height at takeoff is restricted to 0.5m [22].

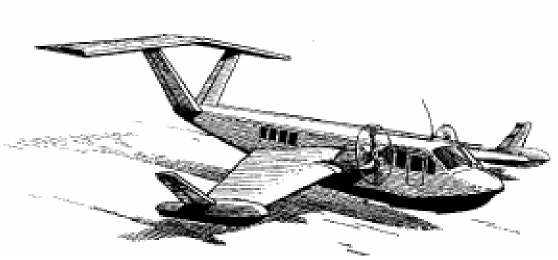

Figure 33: XTW-1 vehicle (CSSRC, Wuxi, China) [22]

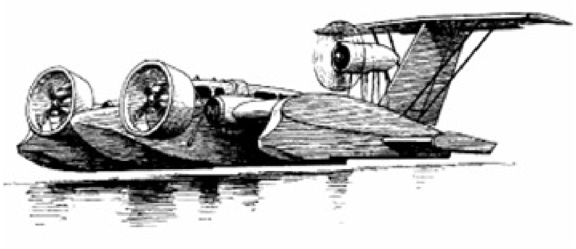

Figure 34: AWIG-751 (MARIC, China) [22]

In 1995 the China State Shipbuilding Corporation Commissioned the R&D for a 20 seat AWIG-751, under the name “Swan-I” to MARIC and the Qiu-Sin Shipyard [22,12]. The AWIG-751 had several new features including an increased main wing span, enhanced longitudinal stability by combined use of guiding vanes and flaps, and new composite materials to reduce structural weight[22]. A follow on model, the AWIG-751G, featured increased dimensions, modified engine layout and an improved composite wing [22].

9.2. Projects in Germany

A German Company Fischer Flugmechanik has recently developed various sports vehicles under the name Airfish. The Airfish series, unlike other sports craft, was designed only to operate in ground effect. The first models (Airfish FF1/FF2) were two seat vehicles and in testing were able to reach speeds of 100km/h at half-engine speed [22,5]. In 1990 a heavier 4-seat model, the Airfish-3, was tested. The Airfish-3 travelled at speeds of 120hm/h and was able to cover a range of 370km [22,5]. The craft, although designed only to operate in ground effect, was able to perform *dynamic jumps* to a height of 4.5m [22].

A later design based on the Airfish series, the Flightship 8 (FS-8), is able to seat eight people, including two crew members [22,5]. The FS-8 has a maximum takeoff weight (TOW) of 2325kg [22]. The wave height at take off is 0.5m but can function in 2m waves when cruising [22]. The FS-8 has a cruising speed of approximately 160km/h and a range of 365km. A larger Flightship 40 (FS-40) is currently being designed. The FS-40 will carry 40 passengers or an equivalent payload of 5 tons in alternative configurations. The cruising speed is expected to be about 225km/h. The FS-40 takeoff wave height will be about 1.2m and the craft will negotiate waves of 4m once cruising. Fischer Flugmechanik has also proposed a craft, the HW20, utilising a combination of WIG effects and static air cushioning technology. It is proposed that the craft that the air cushion will be used only for takeoff, allowing the vehicle to reach a sufficient speed before making use of WIG effects [22].

Another German company, Techno Trans, has proposed developing an 80-passenger ferry under the name Hydrowing [22,6]. A 2-seat prototype (the Hydrowing VT 01) has been built and tested [22]. Techno Trans is presently working on the Hydrowing 06. The designs feature the forward sweep found in the Lippisch designs and utilises both air and water rudders [22]. The crafts cruise speed is expected to be 125km/h [22].

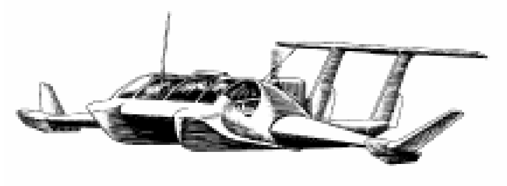

Figure 35: Hoverwing-20 with a static air-cushion lift-off system [22]

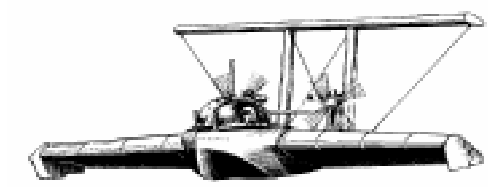

Figure 36: "Hydrowing" vehicle of Technotrans [22]

Figure 37: Airfish 8-Flightship 8 [22]

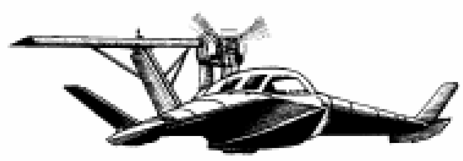

Figure 38: Airfish 3 [22]

9.3. *Projects in Russia*

Russia has been involved in the development a number of WIG effect craft in recent years. Many of these designs are in intended to be used as passenger transportation. Such designs include the Marine Passenger Ekranoplan (MPE) series, ranging in TOW from 100 through to 400 tons [22,26]. The MPE-400 is intended to carry 450 passengers [22]. MPEs' feature S-shaped central wing sections for greater stability [22].

The Amphistar-Aquaglide series is another such transport vehicle developed in Russia by the company 'Technology and Transport'. The Amphistar was built in 1995. The crafts maximum TOW is 2720kg, and has a cruising speed and range of 150km/h and 450km respectively [22]. A modified version of this design appeared under the name of Aquaglide, and various similar scaled designs have appeared since. A 90-passenger high speed river craft called the Raketa-2 has been developed. The Raketa-2 is powered by a gas turbine, and can travel at speeds of 180km/h for ranges up to 800km [22].

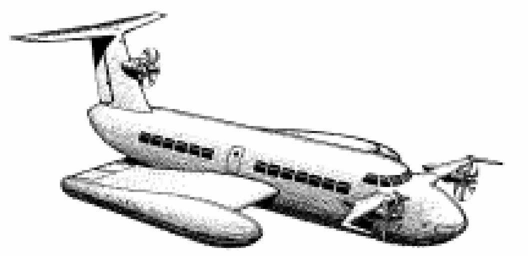

Figure 39: Aquaglide-50 (project, Synitsin, ATT-ATTK) [22]

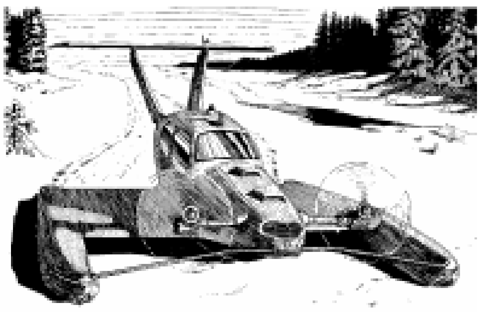

Figure 40: Aquaglide-5 wing in ground effect vehicle (Synitsin, ATT-ATTK) [22]

Russia is also developing a series of so called *Transport Ampibious Platforms (TAP)* that utilise both air cushion technology and WIG effects [22]. It is believed that these vehicles will have numerous advantages over conventional hovercraft. Some such advantageous include higher cruise speeds (about 2x), increased stability in rough seas, higher cargo carrying capacity and weight efficiency, and a simplified structure [22,9].

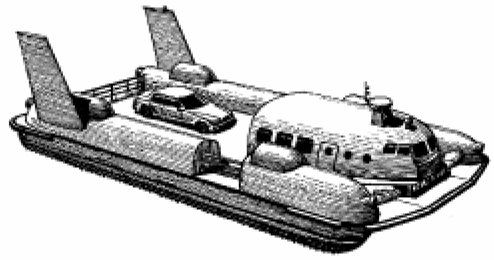

Figure 41: Transport Amphibious Platform (project, CHDB) [22]

9.4. Projects in the USA

In the early 90's, the US company AEROCON developed a large Wingship called the Aerocon Dash 1.6 [22, 2]. This vehicle has a TOW of a massive 5000 tons and is capable of a cruise speed of 400 knots (740km/h) [22]. The vehicle has a cruise altitude of 12ft (3.66m) but also has the unique capability of overground flight at an altitude of about 6000ft (1830m) [22]. The vehicle can reach similar speeds of 400 knots out-of-ground-effect, however, much greater aerodynamic efficiency can be achieved in ground-effect [22].

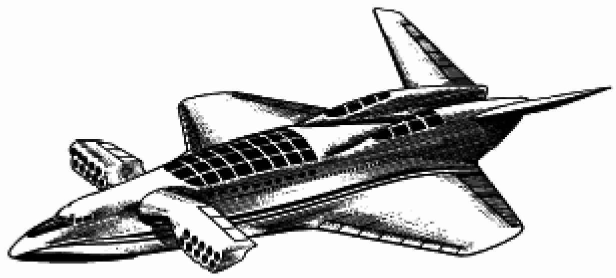

Figure 42: Aerocon Dash 1.6 "Wingship" (Stephan Hooker) [22]

Another US company Lockhead Martin Aeronautical Systems (LMAS) have been investigating vehicles which they call *Sea-Based Aircraft* [22,24]. They are being developed specifically for military use, with the function of moving a small force rapidly to any location anywhere in the world [22]. The designs are a combination of seaplanes, floatplanes and WIG-like combined surface effect aircraft (SEA), although the SEA aircraft are the most promising [22].

Boeing Phantom Works is developing a large cargo craft called The Pelican [22, 4]. The Pelican has a wing span of 0.4ha, twice that of the worlds largest aircraft (the An-225) [22]. The craft has a trans-oceanic range and can fly at in ground effect 20ft but can also fly out-of-ground effects at altitudes of 20,000 ft or higher [22]. The vehicle can be use for both commercial and military operations which require speed and high throughput [22]. The pelican is capable of carrying M-1 battle tanks [22]. The Pelican has other potential applications as a mothership for unmanned vehicles and for piggybacking reusable space vehicles [22].

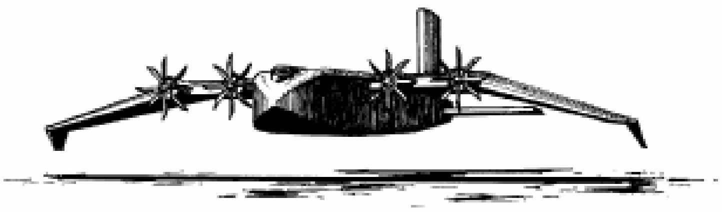

Figure 43: Fig Cargo plane in ground effect concept "Pelican" (Boeing) [22]

10. Conclusion

The benefits of the wing in ground effect have been known and exploited for many years. Yet the dangers and perceived risks of wing in ground flight have held back the design and evolution of WIG craft over many decades. To this day there is relatively little government funding into research and development of WIG craft. Previous developments in WIG craft design have largely problematic and plagued with accidents, yet the accomplishments that have been made have shown that the WIG effect has great potential and that WIG craft can be designed for practical applications. The ability to have the speed of a plane with the payload of a boat has the potential to revolutionise society's means of cargo transport, while the recreational potential of WIG craft remains appealing to many. Despite the troublesome development history of WIG craft and consequent withdrawal of large scale funding, great interest still exists in many aeronautical enthusiasts and academics, who continue to work in order make WIG craft performance acceptable so that they may one day become commercially feasible and successful.

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