Practical Considerations Regarding Wing-in-Ground Effect Aircraft

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Apparent advantages of flight within ground effect have been long known to aircraft designers and aviators. Numerous tests of models in close proximity to wind tunnel ground boards provided extensive data indicating remarkable increases in lift/drag ratios over comparable models out of ground effect. The resulting enthusiasm stimulated numerous studies of very large aircraft intended to operate in ground effect (WIG's). Unfortunately, various practical considerations frequently were overlooked or minimized. Rarely is more than casual consideration given to take-off or landing, except to assume that operation from water is self-evident and achievable. It is demonstrated, using seaplane technology and experience, that hydrodynamic configurations permitting water operations are, for the most part, incompatable with aerodynamic features required for extended flight in ground effect. The installed thrust specified for the WIG's frequently is inadequate to accelerate the craft from rest to take-off. Furthermore, the aircraft must fly high enough to avoid catastrophic encounter with "rogue" waves which are up to three times as high as "significant" waves of the existing sea state. Rogues are infrequent, but inevitable. It is concluded that it is neither feasible to design WIG's for operations from the water nor fly in ground effect over the open ocean.

Introduction

THE concept of intentionally operating suitably designed large aircraft within ground effect has provided the basis for numerous studies investigating performance and economic advantages to be gained from the use of huge "Wing in Ground Effect" (WIG) aircraft flying just above the ocean surface. In general, studies have been based upon analyses, wind tunnel tests, pilots' impressions and recollections, and, as will be discussed, unrealistic and artificial definitions of sea state, ocean waves, and operating conditions.

Each study was initiated by review of wind tunnel data concerning the relationship of wing lift/drag ratios and its proximity to a ground plate. Personal observations of aircraft behavior during the short period of take-offs and landings tend to confirm the desirability of operating within ground effect. After it has been decided that over-water travel is feasible, several routes or missions are chosen, a statistical study of year-round wind and wave conditions made, an operating height above mean water level selected, mission and cost analyses made, and a preliminary design prepared. During these early phases, fundamentally unrealistic decisions often are made, endowing the entire study with a questionable degree of reality.

Wing-in-ground-effect studies generally emphasize the aircraft's cruise characteristics. Virtually no attention is given to suitable take-off or landing requirements or appropriate configurations. It is usually assumed that the aircraft, in an undisclosed fashion, reached cruise speed and altitude before the study began, and the study concludes without bringing the aircraft to rest. As a consequence, little or no consideration is given to take-off and landing problems, restraints or characteristics. Sketches of the hypothetical craft in flight generally show the wing(s) placed to gain maximum advantage from ground effect. However, if the craft is to operate from water, it must be a seaplane – resting on a hull or floats; obtaining dynamic lift from a planing bottom, skis, hydrofoils or air cushion system. Adequate aerodynamic and hydrodynamic stability from stand-still through take-off to flight are necessary, as is acceptably low drag, so that it can, in fact, take off with its available thrust.

Components contacting the water must be structurally capable of withstanding hydrodynamic loads; heavy spray must be controlled so as to not adversely affect power plants, wings, or control surfaces. Personnel must not be subjected to intolerable loads or motions. If the aircraft is to operate from land, these problems are eliminated; others may be introduced by use of wheeled gear.

Effect of Water Take-Off Requirements Upon Design

Model and full scale evaluations of advanced seaplane hulls designed by the National Advisory Committee for Aeronautics and aircraft companies show that a lift/drag ratio of 7 through "hump speed" (the transition from displacement to planing, or static to dynamic support) is about the maximum to be anticipated for calm water. This ratio will rapidly decrease as waves become larger until hydrodynamic drag becomes prohibitive.[1,2] Hump drag establishes the thrust needed to provide reasonable acceleration (3 ft/sec^2 was required for Navy Seaplanes). This thrust largely decides power plant characteristics, regardless of in-flight weight/drag or cruise speed. Unless substantial low-speed auxiliary thrust is provided, installed thrust will exceed cruise thrust by the ratio

$$K = \frac{\text{thrust (hump)}}{\text{thrust (cruise)}}$$

If $K = 5$, for example, 80% of the aircraft's engines will be shut down in flight to conserve fuel but still represent dead weight and aerodynamic drag, detracting from the aircraft's payload and performance. Complete elimination of penalties associated with hump drag could only be accomplished by use of JATO, towplane, catapult, etc., which must be analyzed for cost per flight, capital investment, manpower requirements, useful life, and practicality.

Should the airplane be designed for take-off and alighting in other than calm water, consideration must be given to substantially increased hydrodynamic drag, alleviation of

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wave impacts, heavier structure, human factors, spray suppression, and adequate airframe and engine clearances. It is probable that most problems associated with conventional seaplanes will be intensified by compromises necessary to maximize the WIG's weight/drag ratio.

An excellent example of a preliminary design found to be completely incompatible with water basing was a huge canard with a 300 ft span wing forward and 600 ft wing aft. It was to carry all cargo in, and float on straight wings which had a thickness equal to 30% chord. The untapered wings had no dihedral, so were uniformly immersed over their entire spans when the airplane lay at rest or moved slowly through the water. Results of towed model tests were unexpected; each wing represented, more or less, a barge towed sideways, and as model speed exceeded wave propagation speed, water literally piled up ahead of the forward wing, finally stabilizing in a heavy blanket of water flowing *over* the wing. Drag was many times greater than that of an equivalent conventional seaplane. As the towing carriage accelerated the model, it settled deeper into the water until the power plant locations were submerged. The wing incidence was repeatedly increased, run after run, in an effort to contain the flow beneath the lower surface. This was finally achieved, but the forward wing trimmed to 22°, a completely impractical solution. Bow-down moments due to thrust would have caused the model to dive, except for the restraint of the towing mechanism. These tests did not discredit the aerodynamic design; they demonstrated that this craft could not be water-based, although it may well have successfully lifted from an adequate runway several miles long. Although the structure reflected anticipated air loads, no consideration was given to water loads. If the airplane could have taken off, the problems associated with alighting on the water seemed overwhelming: impact loads intolerable to crew, airframe, and cargo; directional and longitudinal instabilities; and the possibility of a catastrophic water-loop upon contact.

Moments acting on a seaplane during take-off must be in equilibrium. The resultant of hydrodynamic lift and drag produced by the hull, skis, or foils must pass through or near the center of gravity. Seaplane hull steps are located just aft of the center of gravity, so forebody lift and drag will produce a resultant vector just ahead of the c.g., preventing diving and compensating for bow-down moment due to thrust. As the aircraft nears flying speed, hydrodynamic forces decrease and the pilot maintains control by use of increasing aerodynamic forces. The hull aft of the step is sloped upward to clear forebody wake and spray. An afterbody "sternpost angle" of 7.5-10° permits aircraft to trim to a high angle for take-offs and landings without afterbody contact with the water surface – a condition which can cause dangerous and uncontrollable "porpoising." The step must be deep enough to ensure that water from beneath the forebody separates at the step, clearing the after hull. The step break must be sharp; any rounding of the corner makes it ineffective. It was in 1909 that Naval Constructor Holden C. Richardson visited Glenn Curtiss at Hammondsport, N. Y., and after watching a pilot unsuccessfully try to take off, told Mr. Curtiss that his hydro-aeroplane wasn't about to leave the surface of Keuka Lake unless he put a step on the main float. The same basic rules are still valid today, notwithstanding the development of turboshaft engines and aerodynamic high lift devices. The Japanese PS-1 seaplane's maximum take-off weight is about 95,000 lbs. It has an exceptionally high power/weight ratio; thrust is provided by four 3060 hp General Electric T-64 engines. A 1400 hp General Electric T-58 drives the boundary-layer control system. The combination of boundary-layer control and large flaps enables the airplane to take off at less than 50 knots airspeed. Nevertheless, a traditional high deadrise, stepped hull was considered essential. It is inconceivable that a WIG with a low horsepower/weight ratio could operate from the water unless fitted with a correctly designed hull or an alternative hydrofoil system mounted beneath a hydrodynamically compatible hull.

Referring again to the canard design, the aerodynamic, structural and volumetric advantages of a large thick wing or airfoil shaped fuselage are obvious, but the associated convex lower surface represents a very poor planing surface and in no way can be considered to be part of a hydrodynamic system.[3] An air cushion system initially might appear to be a logical installation on a flat bottom, broad beam, barge type hull, but the weight and internal volume of the lift-fan system, associated ducting, skirt or seals, and source of power detract from the useful load; and whether the vehicle planes on a hull of metal or air it still must have enough thrust to accelerate "over the hump." Conventional seaplane hulls and air cushion systems have been compared by detailed studies, including model tests, and the hull was superior to the air bubble configuration in all characteristics associated with aircraft operation from the water.

There is little doubt that almost any conceivable WIG configuration, fitted with a suitable hydrofoil or ski system and propelled by brute force, could take off from and alight on the water. But the weight of alighting gear and necessary engines, volume occupied by the retracted gear, and drag of inactive engines during cruise could well wipe out any virtues of the configuration. It is possible that for many preliminary designs the attainment of adequate hydrodynamic behavior could be achieved only by destroying utility.

Variable geometry aircraft which take off and land with the wing in an elevated position but fly with the wing lowered as far as possible to maximize ground effect have been considered, but the associated complexity, weight, and cost of the installation dictate against this concept. Variable dihedral wings or outer wing panels and end plates which can be rotated through an arc around a longitudinal axis through the extremities of the fixed wing are worthy of consideration.

When a flying boat is envisioned, the design engineer prepares a set of sketches corresponding to successively higher water-borne speeds from the displacement regime through hump and planing to take-off. Each sketch shows the hull's probable trim, heave and corresponding spray pattern, determined either by model tests or tests of a similar hull. The sketches indicate where one should *not* locate the wing, engine inlets, propeller, cockpit, and control surfaces. Heavy spray represents wasted energy (or drag), and will cause additional drag if it strikes any portion of the airplane. Severe spray can reduce propeller speed, slow and even stop turbo-shaft engines and cause structural damage to engines and airframe. After the designer has reviewed his sketches and pondered on the above factors he must decide whether there remain any comparatively spray-free locations permitting a rational design for the objective and mission under consideration. Should it be necessary to locate components in the path of heavy spray, the structure must withstand impacts and steady state loads of air-water mixtures weighing 10-30 lbs per cubic foot, and occasionally having relative speeds as high or higher than vehicle speed.

Virtually all water-based WIG's proposed to date could be reconfigured to operate from runways, ideally located at water's edge to permit the aircraft to take off and smoothly accelerate to cruise condition without leaving ground effect. Excess thrust for acceleration could be minimized by use of extremely long runways, thereby reducing the number of engines shut down during cruise. The corresponding decrease in aerodynamic drag and dead weight would aid the designer in attaining his goal of a vehicle designed for economical cruise, unencumbered by engines required for take-off only.

The Ocean, "Sea State," and Giant Waves

The greatest misapprehension associated with the desire to fly in ground effect over water is the assumption that somehow the sea will concur with the conditions predicted in studies of WIG missions.

Assume that a study of specific areas and trade routes has shown that sea states 4 or less prevail over a percentage of time which makes the WIG economically or militarily justifiable. When higher seas exist, the craft must either be rerouted or fly at a higher altitude with resultant decreased lift/drag ratios and correspondingly reduced performance.

Sea state 4, used as the typical condition for this Section, is *defined* as that condition generated by fairly steady 15-20 knot winds blowing for nearly a full day over an uninterrupted "fetch" of 125-175 miles of deep water. This definition implies that there do not exist other sources of waves or swells: tides, distant storms, strong ocean currents, shallow areas, or significant changes in the ocean bottom. This definition is at best a general description of the state of the sea; it is assigned by an observer, ashore, afloat or aloft. But one cannot assume that the ocean will meet the description of a given sea state merely because it has been so defined. Furthermore, the "sea state" definition, or description, is based on an idealized situation, and variations within a "sea state 4" may fall outside the glibly stated characteristics.

An "ideal" sea state 4, as defined by one source, is characterized by the height of the highest one-third of the waves usually falling between 5 and 8 feet (trough to crest). These "significant waves" are 120-200 ft long. Table 1, from the Navy magazine *ALL HANDS*, includes a broad range of wind and waves within the U. S. Navy Hydrographic Office's definition of sea state 4. Note the accompanying descriptions concerning estimation of wind velocity, and the various descriptive adjectives which the observer uses as a guide to *his* definition.

The purpose of including two descriptions of the same sea state is to illustrate how a preliminary designer, by random or casual choice of a sea state chart, can influence his entire preliminary design study. The engineer who chooses a table or chart providing a mild description will eventually arrive at a higher cruise L/D and a lower cargo cost per ton mile or greater range than the engineer who selects a more severe definition of the same ocean environment.

The above descriptions give different but fairly simple impressions of sea state 4. Hydrographic Office Publication 603[4] gives a more complex picture. It states that an 18 knot wind blowing long enough over an adequate fetch will generate "significant waves" averaging 6.2 ft high. "E" is defined as "twice the variance of a large number of values from points equally spaced in time as chosen from a wave record." "Significant wave height" can be statistically shown to equal $2.83\sqrt{E}$. Other characteristics of the sea having significant wave height = 6.2 feet are found as follows

Most frequent wave height $= 1.41\sqrt{E} = 3.1$ ft

Average wave height, $\overline{H}$ $= 1.77\sqrt{E} = 3.9$ ft

Average height of the highest 10% of all waves, $\overline{H}_{1/10}$ $= 3.60\sqrt{E} = 7.9$ ft

Reference 4 includes a detailed discussion concerning "Exceptionally High Waves," essential reading in any consideration of high-speed operations on or close to the ocean surface. It says that completely unpredictable monstrous "rogue" waves (compared with the existing sea state) can appear without warning at any time; and no matter how rare they may be from a statistical viewpoint, they are inevitable and must be always anticipated. And, it should be added, be regarded with respect and awe. If 1000 consecutive waves in a sea state 4 environment are taken as a sample, 5% will have heights in excess of 2.22 significant wave height. Therefore a craft operating in sea state 4 will occasionally encounter waves approximately 14 ft high! Now restore the idealized sea state to its ocean environment where waves and swells from distant sources may be passing through the vicinity. Recalling that long waves travel faster than short waves, the "exceptionally high waves" just discussed may be elevated further by the passing of long waves and swells, temporarily creating even larger and steeper waves having heights the arithmetic sum of the component waves. Such giants could damage, upset or demolish any WIG striking their flanks. Since one train of waves may be briefly "filling in" another set, the pilot may be misled by the comparatively calm area into a false sense of security, not realizing that within a few seconds a single or several giant waves suddenly will rear up ahead of or beneath him.

Photographs of the sea taken from various altitudes show that the surface often represents the summation of three or four distinct wave patterns. Sometimes patterns intersect and create a confused sea; on other occasions the waves and swells move in the same general direction. The more complex the surface, the more difficult it is to make any judgement of sea state from one minute to the next, and the more imperative it becomes to fly at a safe distance above any possible combination of waves generated by the several sources.

In summary, one must realize that if a substantial sea state exists, sooner or later, an outsize wave will appear without warning, and if the aircraft strikes it, almost certain disaster will ensue. Only by operating above protected and shallow waters, such as the Baltic or Caspian Sea, can the WIG be safe from high sea states and rogue waves; and the need for this type aircraft in such restricted areas is questionable.

Ground-Effect Considerations Regarding Vehicle Configuration

Wing lift and drag vary as a function of height (Fig. 1) as the craft passes over waves and swells. Since only one lift corresponds to aircraft weight, passage over a trough results in a lift deficiency and the craft will accelerate downward. Conversely, passage over a crest causes excess lift and an upward acceleration. Changes in altitude also affect aerodynamic drag, so waves impose longitudinal as well as vertical accelerations and decelerations on the craft. Consequently, the airplane is aerodynamically linked to the ocean surface. Aircraft motions will lag behind the corresponding wave contour; hence, there will be a possibility of the craft simultaneously dropping and trimming downward because of a passing trough, and then striking the flank of the following wave. This situation would be especially dangerous during passage over a series of long, essentially regular swells having length and speed inducing aircraft vertical motions corresponding to its natural heave frequency. It is doubtful if either a pilot or autopilot could counteract wave-induced resonant oscillations.

Craft have been designed which, although stable in ground effect where they were intended to operate, were found to be unstable at altitude. Only a few years ago tests of a large manned model disclosed this inherent limitation to the concept of operating tandem wing aircraft in ground effect: the absence of downwash from the forward wing upon the aft wing permits both wings of a tandem configuration in ground effect to have similar aerodynamic characteristics. This advantage is lost as the aircraft gains altitude, and the intensity of downwash is increased. Within ground effect a craft with identical, equally loaded, adequately spaced, tandem wings should stabilize in altitude, longitudinal trim, and zero roll angle, thereby minimizing the need for an active control system. Out of ground effect, down-wash is so strong that the relative incidence of the two wings must be adjusted to retain their original lift distribution. Consequently, although the craft is inherently stable within ground effect, it rapidly becomes unstable out of ground effect unless the craft is controlled by a system having exceptionally powerful pitch moments.

The experienced and careful test pilot did not realize that his altitude for this flight was to be limited to only a foot or two. As his craft accelerated and left the water, he pulled back on the stick to gain altitude, lost inherent stability due to ground effect, and crashed. The need to stay within ground effect sharply curbs such a ground-effect oriented aircraft's

Table 1 The effect of wind and waves on the sea around you

Wind force (Beaufort scale)	Seaman's description of wind	Terms used by weather bureau	Wind Velocity (miles per hour)	Wind velocity (knots)	Estimating wind velocities on land	Estimating wind velocities at sea	U.S. Navy Hydrographic Office Sea description and wave heights in feet	U.S. Navy hydrographic office sea state code	International Scale sea description and wave heights in feet	International code for state of sea
0	Calm	Calm	Less than 1 mph	Less than 1 knot	Calm; smoke rises vertically.	Calm. Sea like a mirror.	Calm 0	0	Calm Glassy 0	0
1	Light air	Light	1 to 3 mph	1 to 3 knots	Direction of windshown by drift but not by windvanes.	Light Air. Ripples-no foam crests.	Smooth Less than 1 ft	1		
2	Light breeze		4 to 7 mph	4 to 6 knots	Wind felt on face;leaves rustle;ordinary vanes moved wind.	Light breeze. Small wavelets, crests have a glassy appearance and do not break.	Slight 1 to 3 ft	2	Rippled 0 to 1 ft	1
3	Gentle breeze	Gentle	8 to 12 mph	7 to 10 knots	Leaves and small twigs in constant motion; wind extends light flag.	Gentle breeze. Large wavelets, crests begin to break. Scattered whitecaps.	Moderate 3 to 5 ft	3	Smooth 1 to 2 ft	2
4	Moderate breeze	Moderate	13 to 18 mph	11 to 16 knots	Raises dust and loose paper; small branches are moved.	Moderate breeze. Small waves becoming longer. Frequent whitecaps.	Rough 5 to 8 ft	4	Slight 2 to 4 ft	3
5	Fresh breeze	Fresh	19 to 24 mph	17 to 21 knots	Small trees in leaf begin to sway; crested wavelets form on inland waters.	Fresh breeze. Moderate waves, taking a more pronounced long form; many whitecaps, some spray.			Moderate 4 to 8 ft	4
6	Strong breeze		25 to 31 mph	22 to 27 knots	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	Strong breeze. Large waves begin to form; extensive whitecaps everywhere, some spray.			Rough 8 to 13 ft	5

flexibility; it cannot fly over obstacles such as ships; it could not fly from one end of the Panama Canal to the other without "sailing around the Horn;" it could not fly at a safe altitude over stormy seas; and it could not escape land-locked bodies of water. The remedy – a control system embodying variable incidence wings or direct lift control devices – appears extremely complex and would require intensive study relating to the proposed design. It is entirely possible that the tandem wing system must be discarded.

To illustrate the discussion of tandem wing aircraft with a historical note, the Caproni "Triple Triplane" was designed in 1919 with complete disdain for downwash. It featured 8 engines and was intended to carry 100 passengers. It made its only flight in 1921; leaving the water it gained a bit of altitude and then, in the words of Lord C. G. Grey, "slowly and determinedly dove into the sea."[5]

And, finally, the "aerodromes" of Samuel Pierpont Langley were tandem wing affairs. His manned aircraft twice broke up in the air following elevated catapult launchings from a barge in the Potomac River, discouraging him from further efforts to develop a successful flying machine. Dr. Langley, unaware of the structural defects of his aircraft, attributed the disasters to an unfortunate mechanic, whom he accused of permitting the machine to strike the launching device. It is clear from photographs that strong downwash and weak longerons were the real culprits.

The sensitivity of a WIG's lift, drag, and stability to altitude dictates that cruise height be rigidly controlled. Although countless patrol aircraft have flown for many hours at low altitudes, the pilot was free to operate through a range of heights without serious deterioration in aircraft or equipment capabilities. But to fly at a predetermined altitude of, for example, 60 ft with an allowable deviation of ±10 ft is difficult and fatiguing. The aircraft therefore must be controlled by an autopilot. It would be desirable to determine whether height sensors based on hydrofoil craft equipment could be modified for use 40 or 50 ft above mean sea level, or whether completely new equipment would be required.

An alternative height control device has been considered: a highly loaded hydro-ski or super-cavitating hydrofoil mounted under the hull forebody in such a location that it would, upon immersion, impart a bow-up moment to the airplane which nominally would be aerodynamically trimmed with a small bow-down moment. Although use of such a device intuitively appears hazardous, tests and calculations have shown that a useable system could be made up of a foil or ski supported by a base-vented strut.

Ground effect data are presented frequently as a function of wing chord and wing height above the water; consequently, some studies considered low aspect-ratio wings with chords of 100-250 ft. Low aspect ratio wings have poor qualities due to the dominance of the flow by wing tip vortices, so end plates are frequently included, hopefully to induce essentially two-dimensional flow, analogous to flow past an infinite span wing. If end plates protrude below the wing's lower surface, they will be more likely than the wing to strike waves. But

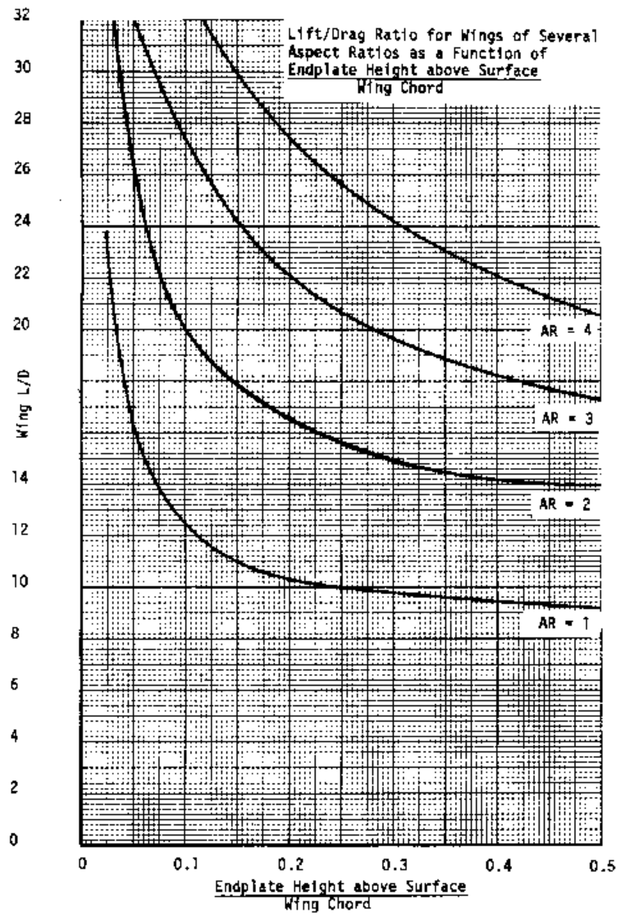

Fig. 1 Lift drag ratio for wings of several aspect ratios as a function of endplate height above surface / wing chord.

while there is little yaw moment resulting from a wave striking the underside of a wing, the forces resulting from contact with the water of an end plate moving at an angle of yaw (caused by crosswind or a turn) would be catastrophic, as indicated in a study conducted for the Navy[6] by General Dynamics to determine the effect of immersing various shaped wing end plates. In general, results showed that there existed a rather depressing option: if the end plate and wing were designed for aerodynamic loads, impact with a wave would smash or rip off the end plate or outer wing panel; but if the structure were adequate, the asymmetric loads could throw the airplane into an uncontrollable attitude, culminating in disaster. It has been suggested that hydrofoils or skis be fitted to each end plate, but analysis of a specific configuration will usually show that this recommendation has little merit because of intolerable forces and moments generated by impact with a high wave or swell.

An alternative to end plates is the use of outer wing panels with rather large cathedral angles to bring the tips sufficiently close to the water surface to minimize the size and strength of wing tip vortices. Since there is inherent danger in the event of wingtip contact with waves, it is recommended that these outer panels be contoured to give hydrodynamic lift from the lower surfaces, and swept aft, to ensure that they not submerge upon contact with the sea. The sweep angle should exceed the greatest possible yaw angle created by cross winds, maneuvers, or a combination of both. Again, hydrofoils, skis, or planing surfaces have been suggested for installation on the outer panels. The panels would be rotatable from the in-flight cathedral position to a level attitude to permit take-offs and landings without immersing the outer wings. Model tests of high performance swept wing aircraft verified the feasibility of using outer wing panels as tip floats. These craft were, however, intended for operation from calm or "sheltered" water. Correspondingly greater buoyancy for WIG's would be required to provide larger righting moments, easily accomplished by increasing the chord and depth of the wing at its tip. Necessary righting moment can be determined from wind tunnel test data of water-line models,[7] or from the old Navy Specification AIR-SR-59C.

Factors Affecting Preliminary Design of a WIG Seaplane

To set all aspects of wing-in-ground-effect operation into consistent perspective, consider a WIG resembling an overgrown conventional flying boat. Once overall weight and dimensions have been selected, it should be possible to decide whether the craft can fly safely and advantageously near the water, or must behave in traditional fashion and fly at a reasonable altitude.

Since "the bigger the ship, the smaller the waves," a choice of 1,000 short tons take-off weight will serve for this study. The airplane would be only 2½ times as heavy as the U. S. Air Force C5-A or the Boeing 747, so it falls within the predictable capabilities of the aircraft industry. Wing loading of 50 lb per sq ft gives a wing area of 40,000 sq ft. An aspect ratio of 4 permits a fairly light wing structure, substantial chord, and reasonably compact span. Use of a 12% Clark Y section ensures good aerodynamic characteristics and useful storage volume inside the wing. The constant 100 ft chord wing would have a 400 ft span, only 80 ft greater than Howard Hughes' HK-4, built of wood over a quarter of a century ago and meticulously preserved in Culver City, Calif. Take-off speed with flaps down will be about 90 knots. Cruise speed will be 150 knots.

Assume endplates projecting five feet below the wing bottom, and define "h" as the distance between the mean ocean surface and the lower edge of the endplate. Wing lift/drag ratio vs wing endplate height relationship[8] is determined to be as shown in Table 2.

Select a modern hull ideal for cruise speeds associated with WIG's. The P5B "Marlin" design represents a good first approximation: length 85 ft, beam 10 ft, deadrise 20°, max. take-off weight 85,000 lb (although the Pilot's Handbook set a lower value). Scaling up the above hull to support the WIG;

$$\left(\frac{20{,}000{,}000}{85{,}000}\right)^{1/5} = 2.85$$

and the new hull is 243 ft long with a beam of 28.5 ft.

The Schoenherr curve is used to estimate the decrease in frictional drag from the P5 hull to the WIG hull, and assuming the usual drag due to spray, an overall lift/drag = 5 at hump appears reasonable. Consequently, required thrust for takeoff, assuming nominal longitudinal acceleration, would be in excess of 400,000 lb, equivalent to about 100,000 shaft hp driving variable pitch propellers designed for 150-200 knot cruise speed.

The hull "beam loading" coefficient is defined as

$$C_\Delta = \frac{W}{wb^3}$$

where W = waterborne weight of the airplane
= total weight minus aerodynamic lift
w = weight of one cubic foot of water
= 64 lb for sea water
b = width of the hull at the step

C_Δ for our 1000 ton vehicle at rest is identical to that of the P5 at 85,000 lb

$$C_\Delta = \frac{85{,}000}{64 \times 10^3} = \frac{2{,}000{,}000}{64 \times 28.5^3} = 1.35$$

The hump speed of WIG is about 50 knots = 84 fps, P5 value $\times \sqrt{2.85}$. The hull trim at hump is about 12°. The speed

Table 2 Wing lift/drag ratio vs endplate height

Height of lower edge of endplate above mean surface	Wing lift/drag ratio
	(Hull, appendages, control surfaces, engines and pods are not included).
10 feet	33
20 feet	27
30 feet	24
40 feet	22½
50 feet	21

coefficient at hump is

$$\frac{G}{\sqrt{gb}} = \frac{84}{(32.2 \times 28.5)^{1/2}} = 2.73$$

Calculations give a maximum spray height of 30 ft at hump. The distance from the center line to the plane at which the spray reaches maximum height is 60 ft.[9,10]

This information tells the designer[11] that the wing must be at least 30 ft above the static water line; and that engines, air inlets, propellers, etc., should be within 50 ft of, or greater than 70 ft from, the center line, since a space between 60 ± 10 ft will be subjected to heavy spray as the hull passes through waves. Again extrapolating from P5 data, the WIG at rest will draw about 14¼ ft, so that the wing's lower surface should be placed about 44 ft above the keel.

Practical experience with the PBY "Catalina," PBM "Mariner," P5 "Marlin," PB2Y "Coronado" and other seaplanes has shown that flight over water can be extremely hazardous if even the lower hull (below the chines) strikes waves. Physical discomfort, structural damage, and upsetting motions are normal consequences. If there is a crosswind, the laterally applied hydrodynamic force can cause the plane to roll, lose a tip float, or fall off into the sea. If contact is very light, the relatively high water velocity can result in a less than atmospheric pressure along the hull bottom which can literally "pull off" sections of plating. This occurred when a R3Y "Tradewind" based at Alameda made a 200 knot-plus emergency downwind landing as the pilot reacted to a runaway engine. The landing was perfect except that many square feet of plating were torn from the forebody; the airplane skipped, touched down a second time, and took on vast quantities of water. Without belaboring the point, it can be stated categorically that aircraft operating at cruise speeds cannot be permitted to contact the water. Therefore, our hypothetical seaplane intended to operate in ground effect over a state 4 sea must fly with its keel at least 20-25 ft above mean sea level to clear not only "outsize" or "monstrous" waves, but also the combination of such waves superimposed upon long ocean swells from distant sources (clearance of at least 30-35 feet would appear prudent).

The lower surface of the wing is now at least 74-79 ft above mean sea level. The end plates extend 5 ft below the lower surface, so are 69-74 ft above the mean surface. Referring to Fig. 1, the L/D of the wing alone, using $h_{\text{average}} = 70$ ft, is about 19, giving a somewhat lower aircraft L/D, within capabilities of modern conventional aircraft flying out of ground effect. If calm sea and zero wind conditions prevail, the WIG could operate with the step just clearing the water surface; h/C then becomes 0.44 and L/D is 22. It must be concluded, then, that only marginal advantages would be derived from a WIG based on the configuration of a conventional flying boat.

Consider how h/C may be further reduced to raise L/D to an attractive value. First, eliminate the seaplane hull; place the fuselage above the wing, bringing about an improvement in L/D as the wing is brought closer to the ocean surface. Assuming that the hydrodynamic or wheel alighting gear can be completely retracted, and considering only the need to clear waves, h/C can be reduced to 0.2 and L/D rises to 27. If an additional clearance of ten (10) ft is considered necessary to permit gradual banking or slight trim changes (required to fly over an obstacle) $h/C = 0.3$ and L/D drops to 24.

If the wing is reproportioned to other aspect ratios, corresponding values of L/D, can be plotted vs altitude, Fig. (1). These values are for the wing only, and would be less optimistic for complete aircraft. Note how the advantages of increasing chord (higher Reynolds Numbers, lower values of h/C, lighter wing structure) are defeated by the aerodynamic deficiencies of the decreasing aspect ratio. A more definitive selection of aspect ratio would be influenced by the complete configuration, end plate and wing tip float weight and drag (inverse functions of wing aspect ratio), tail surface volume and location, engine location and fairing, slipstream over the wing, etc.

Brief considerations of configurations other than the conventional seaplane result in a broad spectrum of characteristics, but all reflect the general tenor of this paper. The hypothetical advantages of operating in ground effect are overshadowed by restrictions on flight and design imposed by the dominant factor – the ocean itself.

The Boeing 747 and Lockheed C5-A provide a basis for comparison with idealized WIG's. One must compare the 475-520 knot cruise speeds of jumbo jets with the suggested 120-200 knot range of hypothetical ground effect types. Even now, follow-on versions of jumbo-jets have been designed and could be put into production if warranted by sufficient purchase orders. Each generation of ever-larger aircraft encroaches further upon the log paper-lined domain of the commercial WIG, forcing its proponents to consider larger and larger multi-thousand ton craft, each so expensive and carrying such incredible payloads that the potential market could be accommodated by a few craft – too few to justify a production line. Since the tons of cargo and the number of passengers on any route are finite, the multi-thousand ton commercial WIG could not economically support regular schedules. Suitable terminals, back-up and support systems do not exist.

Conclusion

A realistic evaluation of potential capabilities vs inherent problems of aircraft intended to operate in ground effect shows the basic concept to be so beset with mutually incompatible requirements and self-defeating solutions that WIG deficiencies outweigh its hypothetical advantages.

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