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Lessons from Five Years of Hovercraft Operations

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Introduction

ONE of C. S. Cockerell's model Hovercraft was demonstrated and tested at the Saunders-Roe Division of Westland Aircraft Limited in May 1957. This was followed early the next year by a series of basic towing tank and free-flight models. The period from the operation of those first models to the full-scale passenger-carrying trials carried out with four types of British hovercraft has been one of pioneering, and, like all such periods, lessons have been learned the hard way, as well as having things go "according to the rule." Since so very much of the basic hovercraft theory and history has already been given,[1-3] we are not going to refer to these aspects at all; rather we will attempt to deal with the effect of operational experience on the practical design and usage of this type of vehicle.

1. Hovercraft Trials Areas and Routes

1.1. Location

Hovercraft of various types are now the subject of intensive testing throughout the world, the countries involved including the United States, the United Kingdom, France, Sweden, and Russia in the Northern Hemisphere, and Japan and Australia in the Southern Hemisphere. The most extensive testing of large craft has certainly taken place in the United Kingdom.

British hovercraft companies and establishments involved in hovercraft development have conducted trials and operated experimental service routes, mostly in the relatively sheltered waters of the Solent between the Isle of Wight and the mainland. The Denny Hovercraft was tested on the Clyde. The first, and so far only, channel crossing by a hovercraft was carried out by the SR.N1 in September 1959. Various fare-paying, passenger-carrying experimental hovercraft services were operated in 1962 and 1963. As part of the British effort, we should also mention the two weeks of demonstration runs in March 1963 given by the SR.N2 on Lac St. Louis, near Montreal. Perhaps the most exceptional part of this demonstration was the traversing of the Lachine Rapids by the SR.N2 in each direction on more than one occasion.

1.2. Sea States Encountered

Short, steep seas predominate in the Solent where most of our trials have been carried out, wavelengths being of the order of 30–50 ft or even less, and seldom more than 4 ft high. In order to get experience of longer seas, the SR.N2 has been operated outside the Solent; in particular, trips were made around the Isle of Wight to get into the open water of the English Channel, and from Cowes to Portland. The latter involved a voyage of 50 miles, of which about 35 miles was in open water. Waves of between 40 and 130 ft long and up to $6\frac{1}{2}$ ft high were encountered with wind speeds up to 20 knots. Fairly severe seas were also met in the Bristol Channel, coupled with strong tides. At this location there was little choice as to the direction at which the seas could be met if the crossing was not to be unduly prolonged; this gave an opportunity for realistic assessment of operating problems.

It should be noted that the results given in this paper were obtained by craft with relatively short skirts, i.e., approximately 18 in. long on the SR.N1 and 2 ft long on the SR.N2. The experience obtained with the SR.N1 modified to take longer skirts does not appreciably affect the conclusions drawn.

2. Hydrodynamic Lessons

Although the hovercraft may be classed as an airborne vehicle, it soon becomes apparent that difficulties await the

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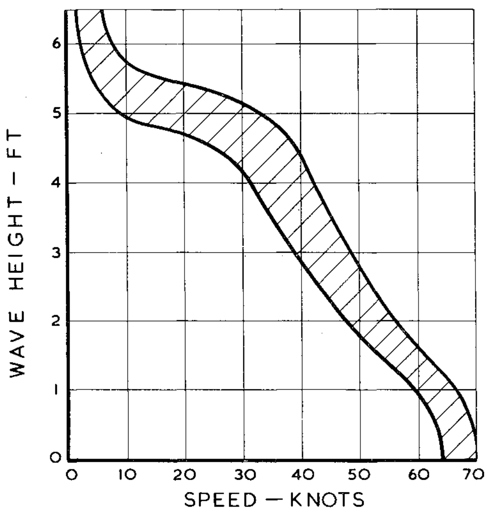

Fig. 1. Speed/sea state envelope.

designer who forgets it is operating in close proximity to a fluid medium over 800 times denser than air, usually far from level and very much more corrosive. At first, we were mainly concerned with calm water performance, the problem of hump drag, stability, trim changes, and, of course, spray. Until 1960 we had little understanding of the effects of operating in rough water and shallow water. These aspects and further observations on the spray problem are dealt with in the following paragraphs.

2.1. Rough Water Operation

As with all marine craft, it is not so much the magnitude of the wave that is important, but the steepness and frequency with which it is encountered. The effect of rough water operation can be considered under three headings: effect on speed, impact accelerations, and effect on comfort.

2.1.1. Effect on speed

When operating in head seas, there will be a reduction in speed which is associated with the need to maintain a limiting acceleration resulting from any impact with the waves. When operating in a downwind, there is also an effect on the control of the craft, and the driver may have to reduce speed further than the speed dictated by water impact so that he retains adequate margins of control. The effects of asymmetrical impacts on the bow quarters associated with a crosswind component is one of the control problems to be solved. In essence, the control power is slightly reduced by the low relative air speed and the reduced thrust required to maintain the given water speed; therefore, a significant water impact on either beam can result in the craft slowing or "pirouetting," as it is described by our test drivers.

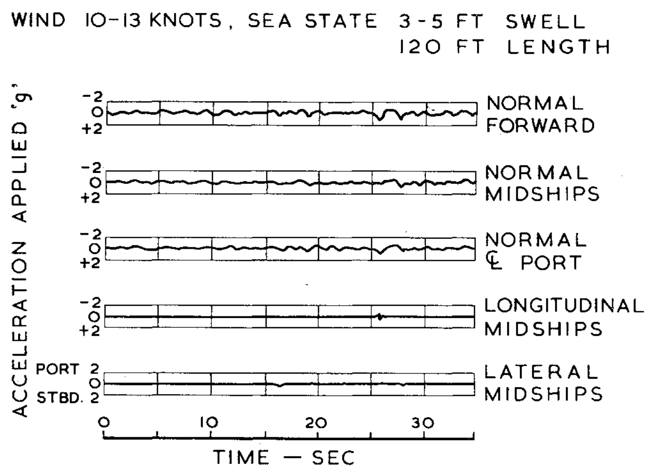

Fig. 2 Examples of accelerations experienced in head seas.

A typical wave height/speed envelope for a 25-ton craft is shown in Fig. 1. This applies to waves near critical length (approximately twice the craft length). In general, the longer the wave the higher it can be, waves of more than six times the craft length having little effect on it. From the diagram, it will be seen that the craft can operate as a displacement vessel in very large seas, has reasonably constant performance at low speed, and then suffers a fall in allowable wave height with speed until at the high-speed end the curve turns down sharply at the maximum-speed point.

2.1.2. Impact accelerations

The worst impacts are likely to result from the encounter with an isolated series of waves, such as the wake of a large ship. An example of hitting an isolated wake train when operating the SR.N2 occurred in June 1962 with the craft at a weight of less than 20 tons and operating at a water speed of 35 knots. The estimated wave height was 4–5 ft and length 100 ft which gave a combined wave/craft speed of 50 knots. In this instance, the peak vertical acceleration recorded by the bow accelerometer was 3.6 *g*. The extremely transient nature of the impact can be judged from the fact that the accelerometer reading returned to zero in less than $\frac{1}{3}$ sec.

The worst longitudinal acceleration occurred during a downwind rough sea trial for strain gage program. No action was taken to reduce speed or impact loads. The craft impacted slewed to starboard and struck the starboard quarter resulting in a positive (forward) longitudinal acceleration of +1.2 *g* at the c.g. Standing personnel were thrown off balance, but seated personnel experienced little discomfort. This case was, of course, unusual in producing a positive acceleration; most other cases recorded have resulted in decelerations of the order of 0.2 *g*–0.6 *g*.

The other form of impact of interest is that due to a "ditching," either deliberately for an emergency stop or due to the failure of all engines. Initial tests by launching a "dead" model by catapult into a ditching tank in the normal flying boat manner indicated very high accelerations (about 12 *g* at the pilot position in SR.N1). When a powered model was used in which the engine was "cut," it was found that the time it took the cushion to decay very appreciably modified the result. When "ditching" from an initial speed of 50 knots, the worst normal acceleration was less than 1 *g* and the longitudinal deceleration about 0.5 *g*. Rather more violent accelerations can be produced on the SR.N2 by cutting the pair of engines supplying power to the forward fan and propeller unit, an unlikely event in practice, since this implies a sudden failure of the transmission. However, this has been tested for certification purposes, and the resulting bow accelerations were within the range $+3\frac{1}{2}$ *g* to −1 *g* and the maximum longitudinal acceleration −0.8 *g*. Note that these largely stem from the nose-down trim caused by the fact that the aft end is still "live" and held up, and the speed

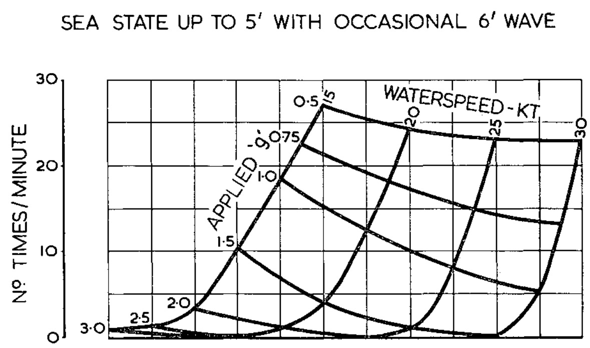

Fig. 3 Frequency of normal impact accelerations vs speed.

is maintained by the active aft propeller until action was taken to cut that half of the system. Even with this treatment the decelerations do not cause distress to the passengers.

A further factor of cushion decay appears in the relatively low-impact accelerations resulting from cutting the engine over the hard standing. With the early SR.N1, which was fitted with steel shoes at hard points on the structure, peak accelerations of only 2 g were registered after cutting the engine at 0.6 ft hoverheight. Measurements of the rate of fall showed that the craft accelerated downward at approximately $\frac{1}{4}$ g instead of 1 g. With the development of skirts, the air trapped by them reduces the downward velocity to a very low figure and consequently reduces the impact.

2.1.3. *Effects on comfort*

As shown previously, in really rough conditions (seas between 4 and 6 ft high), no high accelerations have been recorded because water speed has been deliberately reduced. It is possible for passengers to walk about in the cabin with off-balance tendencies due to the motion, but they are comfortable when seated. In lesser seas with wave heights between 2 and 4 ft and consequently much higher speeds, movement around the cabin continues to be possible, but there is no discomfort to seated passengers.

During the ditching trials, standing "passengers" could be thrown off balance, but seated passengers retained their seats without the aid of seat belts. In general, the degree of comfort in the cabin is fairly high and was commented on very favorably by passengers during the periods when fare-paying, passenger-carrying trials were carried out. The very low incident of "sea-sickness" was from the one or two passengers who looked rather pale before they stepped on board and would have been sick under any circumstances.

Figure 2 shows a typical trace taken during the Portland trip when the craft was heading into a 3 to 5 ft swell at 30 knots water speed. It was from records like this that Fig. 3 was prepared. This shows the frequency of normal accelerations vs speed measured by the forward accelerometer (crew compartment position). The associated accelerations in the main cabin are noticeably less (see Sec. 3).

By and large then, the hovercraft has had a good passenger reaction with the degree of motion so far experienced in rough water. We do not yet have experience that will show the effect of displacement running for a long time, or of prolonged sorties at high speed in open water, such as will be met by naval crew.

2.2. *Shallow water operation*

A hovercraft may well have to operate over shallow waters if full use is to be made of its versatility, as shown by the operation of the Vickers VA.3 in the Dee Estuary in 1962. By shallow water we imply water of less than half the craft length in depth. Theoretical investigation into this problem indicated that the wave drag at the "hump" would greatly exceed that occurring in deep water operation (Fig. 4). If this was so, then most hovercraft of conventional characteristics would not be able to accelerate through the hump region.

Experiments with the SR.N1 showed that there was an increase in wave drag, but that this was not so much as theory indicated. In addition, experiments showed that there was a critical depth of water below which the wave drag was reduced. Also observed was the phenomenon of a very steep wave ahead of the craft when operating in water of approximately the same depth or less as the "hole" generated by the cushion. This wave, which is much steeper than a normal breaking wave, can cause an increase in drag by wetting on a bluff-bowed craft, although not sufficient to be of any great significance on any but very marginally powered craft.

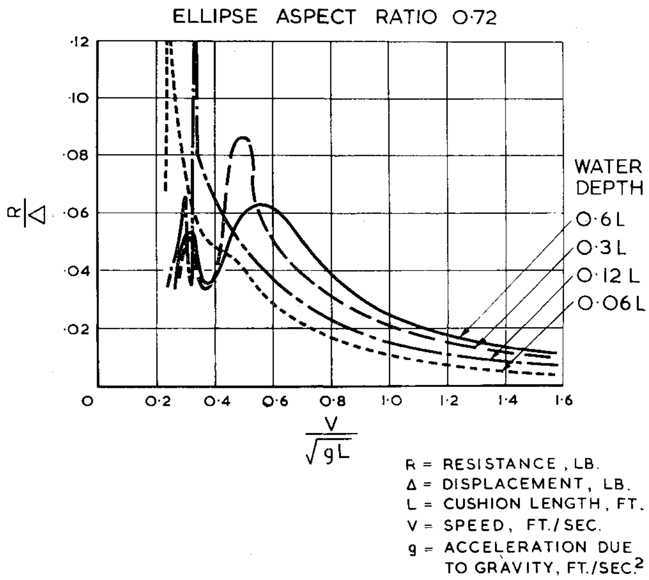

Fig. 4. Theoretical shallow water drag.

The shallow-water drag problem was analyzed by model tests, and the results given in Fig. 5 are typical. It will be seen that below a depth of 0.6 L the hump drag for that particular craft length increased and then fell off again in shallower water. The sharp peaks predicted theoretically are not generated; in fact they were flatter than the deep water peak and occurred at a lower value of $V/gL^{1/2}$. An explanation for this has been put forward in unpublished work by H. Hogben of the National Physics Laboratory, Feltham, in which it is suggested that there is a wave steepness limitation for each depth of water which effectively prevents the peak values from being generated.

From the foregoing, we may conclude that the wavemaking resistance obtained from three-dimensional theory may be expected to predict the actual value experienced at the main hump and above for water depths that are not too shallow in relation to the craft length. The most critical depth should not, in practice, cause an increase of more than 10 to 20% of the deep-water hump wavemaking resistance.

2.3. Spray

The supporting cushion is contained by a jet system having a mean velocity of 200–300 fps, and a by-product is the generation of spray overwater (or of a dust cloud overland). Because of scale effects, this feature is not reproduced in tank tests, although its presence was predicted before full-scale testing took place.

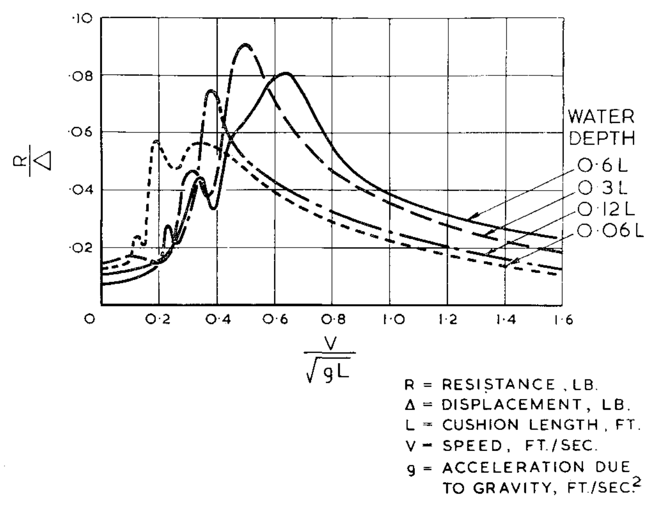

Fig. 5 Experimental shallow water drag.

Attempts to lessen it by using a recirculation system were only partially successful. Tests were made on an overwater rig that had a large "recovery duct" through which the cushion air could be expelled and used to propel the craft. Valves in the duct allowed it to be shut off. Although a marked reduction in spray was achieved as shown (Fig. 6) by these "full-scale" tests, the losses due to the wetting of the ducts resulted in only small gains being registered over water, whereas larger gains were obtained in overland tests by using recirculation. In the latter tests, operation of a recirculation system showed that dust and small stones can be highly abrasive.

Attempts to fit spray deflectors to prevent the spray rising have had limited success, and it has proved difficult to retain them when operating at high speed.

Therefore, since that first full-scale hover in 1959, we have had to learn how to deal with spray since we have not overcome it. Operation at slow speed is best avoided unless it can be done as a "boat"; at high speed the spray tends to go round the craft as shown in Fig. 7. Even so, there is enough close to the craft to demand efficient separation before allowing air to enter the engine air intake. This can be done by momentum separators combined with wire gauze "filters" which condense the spray and allow the water to be drained overboard. There is some evidence to suggest that, even so, a small amount of salt still gets through in the form of particles and for this reason regular engine washing when operating over salt water is practiced.

In spite of a carefully arranged drill, there will be times, such as when accelerating up a slipway after boating through the harbor, when the whole craft is covered with spray. It is at this time that the designer finds out if all surfaces are self-draining, or whether hatches to the engine room and other low-pressure areas are leakproof or not (usually not to begin with!). On a more serious note, tests during the extremely cold spell in January 1963 showed that only during static hovering did ice build up on the outside of the craft when operating in icing conditions, and the air filters tended to pack with slush from frozen spray. For regular service under these conditions, it may be necessary to fit some form of de-icing system to the filters. The external ice built up only slowly, and could probably be removed by the application of suitable fluids at the base stops.

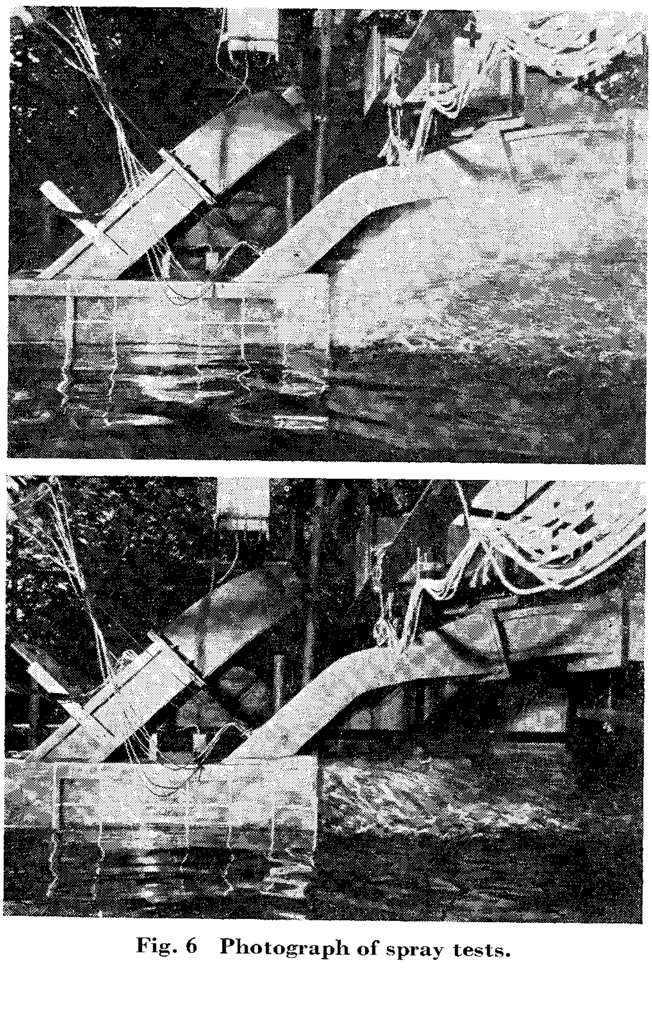

Fig. 6 Photograph of spray tests.

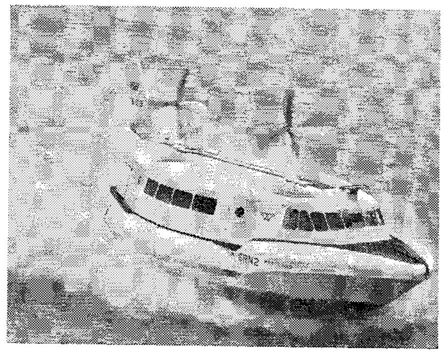

Fig. 7 Photograph of SR.N2 at speed showing spray pattern.

3. Structural Materials and Behavior

3.1. Materials

So far all Westland hovercraft have been constructed of typical aircraft materials of the older and well-established types. A list of typical materials and their properties is given in Table 1. It will be seen that they have been chosen for relatively high strengths while having good corrosion resistance and ease of manipulation.

Investigation has shown that none of the other approaches are economically justified for high-performance hovercraft, e.g., wooden, steel, or glass-fiber reinforced plastic construction. By economically justified, we mean that the weight and cost must be balanced against the performance (work capability) of the craft. Neither is there any call for the use of sophisticated high-strength alloys now finding their way into aircraft use. The use of low-strength weldable aluminium/magnesium alloys as used in boat construction is also ruled out for reasons of weight penalty.

Magnesium is one of the "standard" materials that we have so far avoided. Although a magnesium gearbox casing or other component can stand a marine environment when perfectly protected by modern surface finishes, damage to the protective coating in service will cause rapid deterioration and corrosion to take place. The cost of maintaining the necessary standard of protection as determined by helicopter experience was considered too great for hovercraft application where regular immersion in salt water is a normal occurrence.

The corrosion of high-grade aluminium alloy structure, such as a buoyancy tank, can be avoided almost completely if the manufacture is to the necessary marine standard. This was shown on the SR.N1, which was "opened up" for modification after $2\frac{1}{2}$ years of operation. The inside of the watertight compartments were clean and free from damage, although several had contained a certain amount of sea water at some time or the other. It must be remembered that we are considering structure with thin skins (0.02–0.04 in. thick) supported by light extrusions or folded plate members and not sprayed or otherwise coated internally with a plastic covering as used in integral fuel tanks. Experience with SR.N1 and SR.N2 has shown that, with proper design and assembly, these components remain tight and dry in normal service, but that leaks can result from damage or frequent operation in rough water; and when this occurs it can be very difficult to cure. Therefore, an adequate means of draining or pumping (bilging) each compartment is essential.

Table 1 Material specifications

Material	Specification	Specification values: 0.1% proof stress, tons/in.^{2}	Ultimate tensile strength, tons/in.^{2}	Elongation, %	Application
Aluminium alloy sheet	L.73	21	27	8	Plating, folded stringer and stiffener sections
Aluminium alloy extrusion	L.65	24	28	8	Boom flanges, web stiffeners
Aluminium alloy bar	L.65	24–28	28–32	8	Machined fittings
Aluminium alloy tube	L.63	23	29	6–10	Roof box beam support tubes, struts
Mild steel sheet	S.510	16	28	20	Welded cleats and shoes
Carbon-manganese steel sheet	S.514	40	50	12	Shear bracing end fittings welded to tubes
Steel bar	S.96	43	55	18	Machined fittings, bolts
Steel tube	T.45	40	45	...	Shear bracing tubes welded to end fittings

3.2. Structural Behavior

3.2.1. General

Operational trials of the SR.N1 and SR.N2 (particularly the latter), investigations into damage suffered during testing, published information on damage to other makes and project studies into larger craft, lead us to the following conclusions.

1) The hovercraft has a high degree of inherent safety and can be operated in extremely rough sea conditions without danger of the craft breaking up, although local damage may be suffered by the light peripheral structure in extreme cases.

2) The severity of the impacts due to a power failure or loss of control over water are of such a low order that free-sitting passengers and crew are unlikely to be disturbed from their seats.

3) Stresses due to displacement conditions are much less than the dynamic loads for small (i.e., up to 50 ton) hovercraft, but for large craft (greater than 200 tons) they may be critical in the longitudinal bending case.

4) Although little is known of the effect of a "ditching" overland, it is considered that, where these vehicles are designed for this role (army logistic support?) rather than as amphibious craft with limited overland capability, a suitable combination of skirt and skids should enable them to come to a halt without danger when operating along a cleared trackway or over reasonably level country.

5) The possibility of a collision with another vessel or with a "solid" object such as a buoy, pier, or breakwater is remote, but in such an event it is considered that the relatively light structure is likely to dissipate the energy at the point of impact. For instance, if a collision occurs at 25 knots and the craft is brought to rest in 10 ft (e.g., by the bow structure collapsing), then a deceleration of less than 6 g is involved. The relatively rapid loss of speed of the craft when "ditched" combined with a high degree of maneuverability (see Sec. 6) means that high-speed collisions can be avoided.

3.2.2. Results from SR.N1 and SR.N2 trials

In more detailed terms, evaluation of the structural behavior of the SR.N2 during its trials has shown the following.

1) The method for determining the design impact loads derived by Westland Aircraft Limited and incorporated in the British Civil Air Cushion Vehicle Safety Requirements has been shown to be satisfactory for flat-bottomed craft such as the SR.N2.

2) For seas up to 6 ft high the stresses in the primary structure of the SR.N2, when operating as a displacement vessel or as a hovercraft, are very small and were not greater than one-quarter of the estimated failing stresses. In fact, within the craft's operational capability there appears to be no sea limitation imposed by the primary structure.

3) When interpreting test results from accelerometer records, the elasticity of the craft must be taken into account, since structural deflections have been found to have a noticeable influence. The magnitude of the applied loads are naturally not affected by these deflections, which are very small.

4) The peak water pressures on the SR.N2 lower bow so far recorded are 15–28 psi. The maximum pressure recorded at any point on the bottom is less than 5 psi.

5) The low ratio of pitch to heave of the SR.N2 accelerations indicates that the points of impact occur well aft of the most forward position assumed for design purposes.

6) The low water pressures indicate that the water impact load is well distributed over a large area.

7) There is evidence that flexible skirts greatly reduce the magnitude of the bottom pressures.

Point 3, which refers to accelerometer records should, perhaps, be explained in more detail at this point. Figure 8 shows the location of the six accelerometers on the SR.N2, four of which were used for measuring normal accelerations and two for lateral and longitudinal accelerations, respectively. If at one particular instant in time the accelerations recorded by the three normal accelerometers on the centerline are plotted, the curve is obtained, as shown on Fig. 9a, although from "rigid craft" theory an impact should give a straight line as shown by the modified curve, (Fig. 9). It is considered that this bending can result only from craft deflections, which, although small, appreciably affect the accelerations measured. The maximum lateral accelerations derived from an analysis of the rolling and yawing motion of the craft was at no time greater than 1 g, well within the minimum design value of 3 g.

4. Lift and Propulsion Machinery

4.1. Fans

The SR.N1 is fitted with a 7-ft-diam, six-bladed, axial fan of wooden construction built by the Airscrew and Jigwood

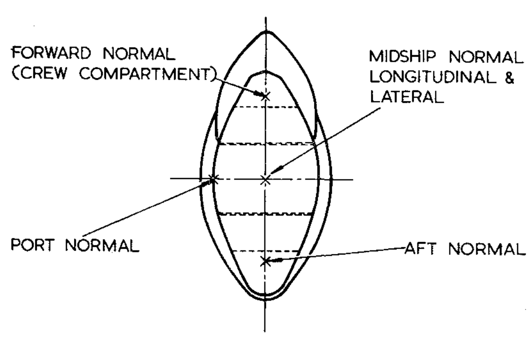

Fig. 8 SR.N2, location of accelerometers.

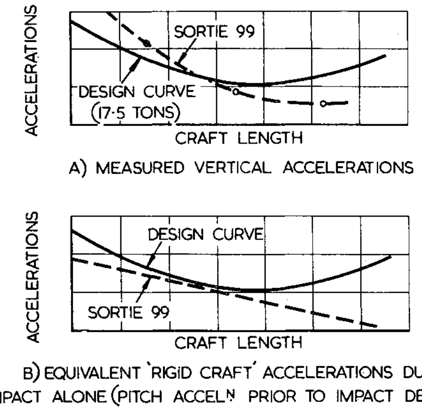

Fig. 9 SR.N2, vertical accelerations due to wave impact.

Company. This fan has given excellent service, the only modification required being the addition of stainless steel anti-erosion sheaths to the leading edge of the blades. The only real problem was raised by the ever present difficulty with axial fans of tip clearance. Originally, the ring around the fan was braced to the engine on which the fan was mounted in order to preserve small tip clearances, the net result being rapid fatigue cracking of the ring and bracing tube ends. The design then was modified to leave the fan operating in a groove with tip clearances of the order of $\frac{1}{2}$ in., as shown in Fig. 10. This allowed for the movement between the engine and the intake "chimney" which occurs during impacts.

On the SR.N2, the fan design was changed to the centrifugal type mounted directly on the buoyancy tank. This fan, which is shown in Fig. 11, has a peak efficiency of over 85% and avoids the losses associated with the axial type when turning the air into the plenum chamber at high velocity; it also provides extra deck space and the added safety feature that the rotating mass is not in line with the passengers. The major problem of designing and manufacturing a $12\frac{1}{2}$-ft-diam fan capable of absorbing 1500 shp for the scheduled weight broke new ground, and this was undertaken by the Saunders-Roe Division of Westland Aircraft Limited. These fans have functioned very well, the only damage to date being confined to the trailing edge of the aft fan blades that were bent by water swirling over the aft end of the buoyancy tank during one of the more severe ditching trials.

4.2. Propellers

The SR.N2 is propelled and steered by two 10-ft-diam, four-bladed, Rotol propellers mounted on pylons which can be swivelled through ±30°. The axes of the pylons, which are 24 ft apart, are directly above the fan centerlines, as shown in Fig. 12. The propellers are modified aircraft propellers having light alloy blades and a hydraulically operated pitch change mechanism in the hub by which the driver can select pitch angles from +45° to −38°. Each propeller and fan are geared to each other and to a pair of free turbine engines, the power split between the propeller and fan being determined by the selected propeller pitch that automatically determines the joint fan/propeller speeds. Thus, at the hover about 90% of the power can be fed to the fans, whereas at high speed 50% or more is fed to the propeller. This system is termed integrated "life and propulsion" and was devised to make the most efficient use of the installed power and to give the greatest degree of safety and flexibility with the smallest number of engines. As already shown in Sec. 2.1.2., it is preferable to safeguard against a power failure at the front fan, as it results in a more severe ditching case, and if one engine of the pair fails, then the other will continue to supply power to the fan.

Therefore, the environment in which we found ourselves operating propellers differed from that of propellers installed on aircraft in the following respects: 1) one propeller generally has to work wholly or partially immersed in the slipstream of the other, 2) large angles of yaw can be induced by the rotation of the pylons or by the side-slipping of the craft as a whole, 3) in an integrated system the propellers have to work over a much wider speed range than is normal to aircraft practice, 4) intricate pitch locks are not required, since the propeller cannot be oversped without a double mechanical failure elsewhere and an accidental pitch change is not too serious.

The main problems have been concerned with vibration and propeller fatigue life for which forementioned point 3 is by far the most important; therefore precautions have to be taken to avoid operating in the region of the '2P' propeller resonance, the position of which is shown in Fig. 13. For operation as a boat, the speed has to be kept in the range 880–1030 propeller rpm to avoid both the red band and liftoff; it is particularly necessary to prevent the speed dropping into the red band because of the application of increased propeller pitch. With later designs, such as the SR.N4 and SR.N5, it has been arranged that the liftoff is below or in the red band, thereby putting the boating firmly below the red band and the hovering conditions well above it.

Although slipstream effects and yawing of nacelles combine to produce a generally "rougher" environment than in aircraft installations, these are not really significant in terms of induced propeller stresses. However, the severity of the stresses in 2P resonance is accentuated if the propeller in question is working in the slipstream of the other—in particular, if the other propeller is running at twice the resonance speed, then the stresses would reach a dangerous level, and this condition must be avoided at all times.

The other difference between hovercraft and aircraft operation is, of course, that the propeller is operating for

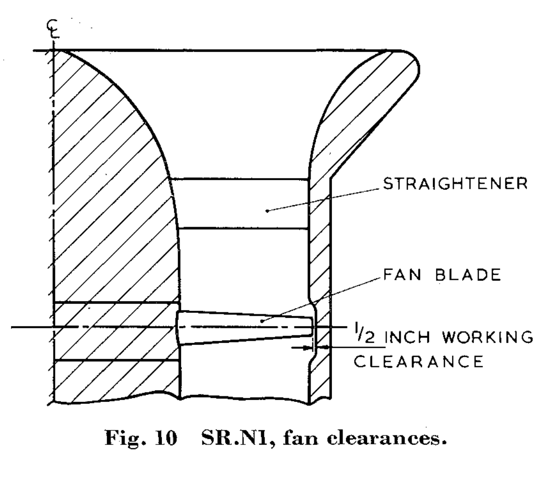

Fig. 10 SR.N1, fan clearances.

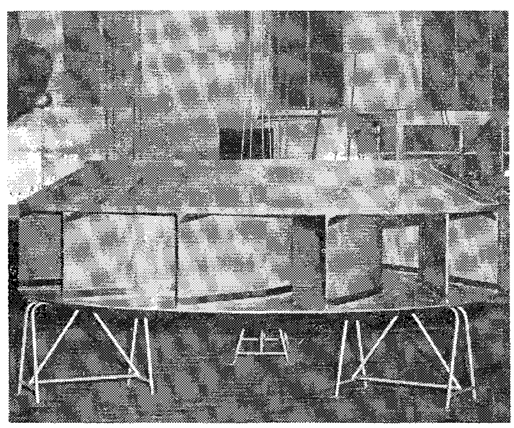

Fig. 11 Photograph of SR.N2 fan.

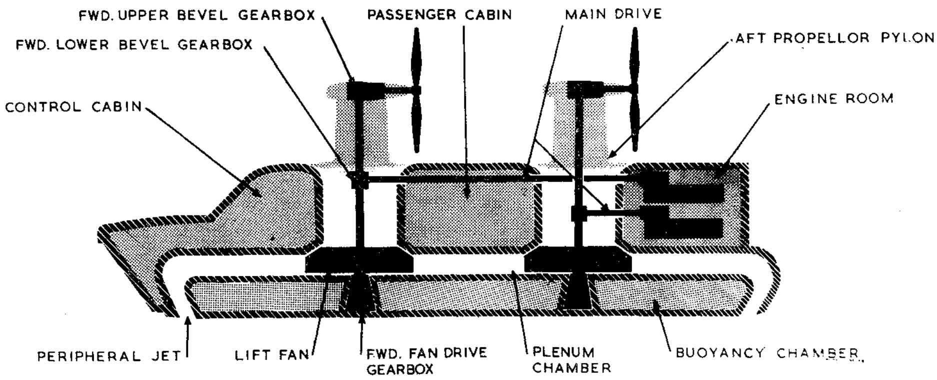

Fig. 12 Diagramatic arrangement of SR.N2.

much longer periods in spray or dust-laden air. This caused erosion to take place on the propeller leading edge, a difficulty that was overcome in the case of the SR.N2 by sheathing the leading edge in polyurethane.

4.3. Powerplant and Transmission

It is probably true that most future hovercraft fitted with gas turbine engines will have the engines installed in an engine room in the manner of a high-speed surface vessel than in individual nacelles as with an aircraft. The reason for this will be to achieve ready accessibility to the engines and to keep them in as salt free an environment as possible.

Even so, experience with the SR.N1 and SR.N2 has shown that great care must be taken in the standard of surface protection and particularly in the sealing to safeguard the engine and auxiliaries against salt. The engine room type of installation implies that there will be large access hatches and also a depression in the engine room of several inches of water when the engines are operating. This condition leads to a difficult problem, as it will soon be found that unless the seals are really good, water is sucked in through the hatches. This undoes the work of the filters that remove practically all the salt water which would otherwise be drawn in with the engine air.

The power from the engines is transmitted to the fans and propellers through a system of shafts and gearboxes. (Studies into hydraulic or electrical systems have so far failed to show that these approach the mechanical system on grounds of efficiency, weight, or safety.) The SR.N2 transmission, which was designed with an extensive background of helicopter work, has proved very satisfactory in practice. One or two points that have arisen during the trials program are, however, worth mentioning.

The first was the fact that the oil temperatures at the entry to the oil cooler were very much lower than expected, permitting the installation of a very much smaller and lighter cooler. The reason for this was found to lie in the use of a centralized oil system that necessitated long pressure and scavenge pipes to the various gearboxes; these pipes were, in fact, acting as the oil coolers.

On the other hand, the reverse was experienced on engine coupling boxes, which were located aft of the firewall and well boxed in. By venting the gearbox bay with blast air from the plenum chamber the bay temperature was reduced by 50°C and the oil outlet temperature from 120° to 90°C.

With both the powerplant and transmission, the problem now is to demonstrate not that it works but that it is safe and reliable and has a suitable overhaul period (time between overhauls). The target for this is at least 1000 hr on the next generation of hovercraft. This can only be achieved by good design coupled with vigorous and extensive operation. When this is achieved, then a large step forward will have been taken in the economic application of hovercraft.

5. Economics

5.1. Capital Cost

The hovercraft designer is often asked why a marine craft such as the hovercraft cannot be produced by shipbuilding methods and at shipyard prices.

We think we can see only limited gains in this direction. Essentially, the hovercraft is a low density craft, as shown by Fig. 14. This shows that in spite of keeping the cushion pressure reasonably constant at a fairly high figure for the craft plotted, the density actually falls with size, i.e., the greater headroom, together with the deeper plenum chamber and buoyancy tank more than counteract for the greater spans and heavier members. It was also found that the structure of the large craft could be made more efficient, resulting in a fall of percentage structure weight with size (Fig. 15) until the effect of very large sizes causes it to rise again. However,

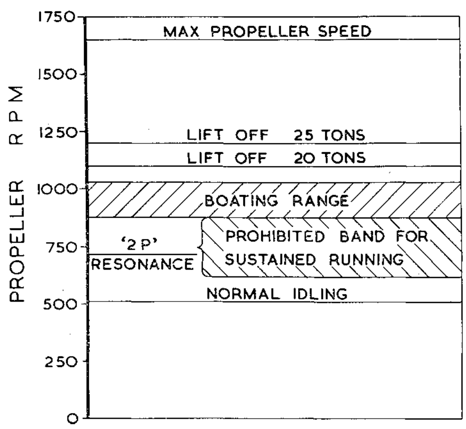

Fig. 13 SR.N2, propeller speed operating conditions.

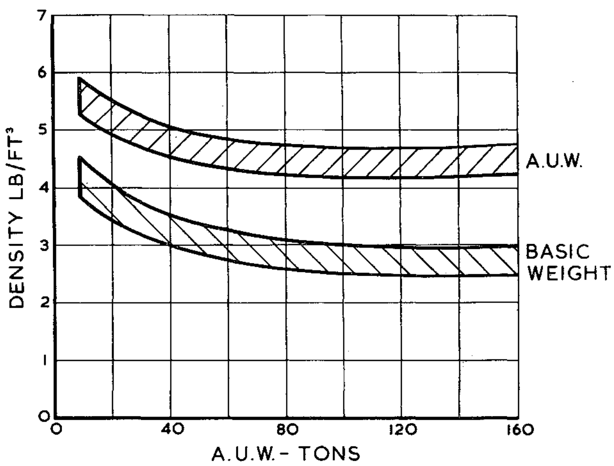

Fig. 14 Hovercraft density vs all-up weight (AUW).

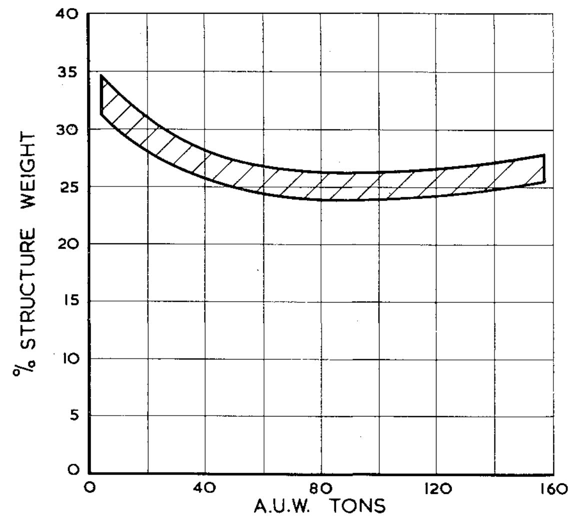

Fig. 15 Structure weight as percentage of all-up weight vs all-up weight.

this result depends on designing the craft down to the imposed loads and not to an arbitrary set of rules or constructing it in a "cheap and cheerful" manner, e.g., of $\frac{3}{16}$-in.-thick, low-grade aluminium alloy welded together in the manner often used to construct "lightweight" superstructure for small ships. For instance, the bottom scantlings of the 25-ton SR.N2 and a 150–200-ton machine would be remarkably similar despite a sevenfold increase in weight.

Nevertheless, a certain amount of simplification can be introduced, such as the use of flat planes or single curvature wherever possible, avoiding countersunk rivets or expensive blind fastenings unless absolutely essential, and keeping to the minimum of standard extrusions, rolled sections, and plate gages.

In addition to the points mentioned, every effort must be made to reduce mechanical complexity and to avoid the use of unnecessarily refined equipment. This is particularly true of small hovercraft where the power/weight ratio is high and the cost and weight of equipment is disproportionately large. Therefore, on the SR.N5 the use of swivelling pylons was avoided and the lift and propulsion derived from a single fan and propeller. Automotive-type equipment is employed wherever possible, consistent with safety and seaworthiness. Above all, the unit cost can be reduced by building in quantity; perhaps again we should think in numbers between ship and aircraft practice.

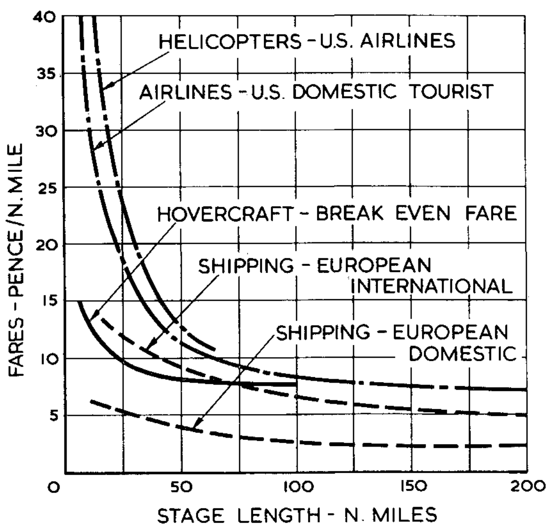

Fig. 16 Fare comparisons.

In the writer's experience, one of the major difficulties encountered arises from the fact that these vehicles are usually designed and constructed by aircraft companies. At first, it is often very difficult to get detail aircraft thinking out of the system, even where the basic design is quite crude, e.g., for some time the detail design of the structure is more refined than it need be. Experience has shown, however, that this way of thinking can be overcome and a cheaper but still highly efficient structure produced.

5.2. Total Costs

The total cost of running a vehicle can be split into two main components, direct operating cost and indirect operating cost. In turn, the direct operating cost may be broken down into 1) annual costs, i.e., amortization, interest, and insurance cost (including spares); 2) maintenance costs, i.e., labor and materials for inspection, maintenance, overhaul, and repair; and 3) operating costs, i.e., crew, fuel, and oil charges plus any station, landing, or docking charges.

We have just dealt with the possibility of reducing point 1; with regard to points 2 and 3, most of the early attempts to calculate operating costs of hovercraft were based on typical airline formulas, such as the International Air Transport Association, Society of British Aircraft Constructors or British European Airways. What little operational experience we have had so far suggests that these formulas over-rate the maintenance and crew costs by a fair margin. Because there is very little, if any, highly stressed structure, no complicated landing systems (flaps and undercarriage), simpler control and instrumentation, and inherent safety in operation, inspection and maintenance is not so critical. Crew requirements are less highly specialized. On the debit side we must have gearboxes and fans; the main answer here is to obtain a reasonably long overhaul life, as already discussed in Sec. 4.

Indirect costs cover such items as sales commission, advertising, passenger handling, administration, base costs and training, and, although not directly affected by the individual characteristics of each craft, they must inevitably reflect the degree of complexity of and skill required to operate the system. Thus, the indirect costs for airlines are approximately 100% of the direct operating cost, those for a bus service only 25%. For passenger hovercraft we would suggest an indirect cost level of 40–50% of the direct operating cost, although there is, of course, no statistical background for this so far.

If then one assumes that indirect costs are 50% of the direct operating cost and that the average load factor will be 50%, i.e., on the average half the seats will be filled, then the break-even fare is three times the direct operating cost. The amount an operator can charge more than this will be profit.

Based on cost calculations, modified to what we believe to be the right order, we have constructed a break-even fare vs stage-length curve for a typical 100 seat, all-passenger hovercraft ferry having a cruise speed of 75 knots, 2000 hr/yr utilization, 50% load factor, and an amortization of 7 years. This is compared with typical airline and shipping fares in Fig. 16. We can see that it is highly competitive with airline and helicopter rates and international shipping. We should point out that we do not know the break-even load factor for the shipping; it may well be considerably less than 50%. Against this the more frequent and much faster hovercraft service is bound to attract more traffic and the smoother flow will reduce customs difficulties and hence add still more to the over-all reduction in journey time.

6. Operational Problems

6.1. Marine Handling

To the hovercraft enthusiast, the mention of marine handling (i.e., mooring, anchoring, towing, and tying-up alongside piers or pontoons), is like talking of cross-country work with the family car, i.e., just not the thing to do. But experience has shown that if the hovercraft is to be operated in conjunction with existing terminal facilities, and to begin with this will often be the case because of the traffic potential, then it will sooner or later be treated as a boat. This was amply demonstrated by the SR.N2's Canadian trip where it had to come alongside a dock wall on two occasions. The blistering remarks of one of the crew who was almost "done to a turn" by the exhaust of an engine that was started up while he was trying to "let go aft" were not easily quelled by an explanation that that particular bollard was only fitted to enable an inoperative craft to be handled by surface tugs in an emergency.

Therefore, although we must weigh carefully the penalties imposed by the installation of adequate marine gear, it is clear that consideration of these problems in the early design stage can reduce these penalties to a minimum.

The other aspect of marine handling concerns the use that can be made of water drag to improve the performance of the craft with respect to braking and turning. For instance, at 50 knots the distance to come to a halt may be reduced in an emergency to one-third of the normal distance by using the skirts to decelerate the craft, i.e., a gentle ditching. Similarly, the turning radius can be halved by immersing the inward skirt. These two factors mean that compared with normal displacement craft, the maneuverability and stopping ability of a hovercraft are extremely good.

6.2. Ground Handling for Construction and Maintenance

This is one of the most controversial items that arises during the preliminary design stage. The approach can be different according to the size of the vehicle, what base facilities it is to have, and whether or not it is multi-engined. Basically, the problem is to balance the weight and cost penalty to the craft plus the cost of the handling devices against possible savings in time and maintenance costs brought about by easy ground handling. Also, there is always the problem of what to do with a "lame duck" that may be towed in.

The first solution by Westlands was, in the tradition of flying-boat design, to provide four, single-wheel, lightweight beaching chassis (later termed ground handling chassis) that were attached manually to the four "corners" of the SR.N1. This served all cases since there is a very good 1:10 slipway which, even with neap tides, has over 100 ft exposed at low water. Therefore, a "dead" hovercraft could be positioned above the slip near high tide and the chassis fitted, the craft being left high and dry as the tide receded. With the SR.N2 the chassis could only be fitted after the craft was clear of the water.

Fig. 17 Photograph of SR.N2 on chassis unit.

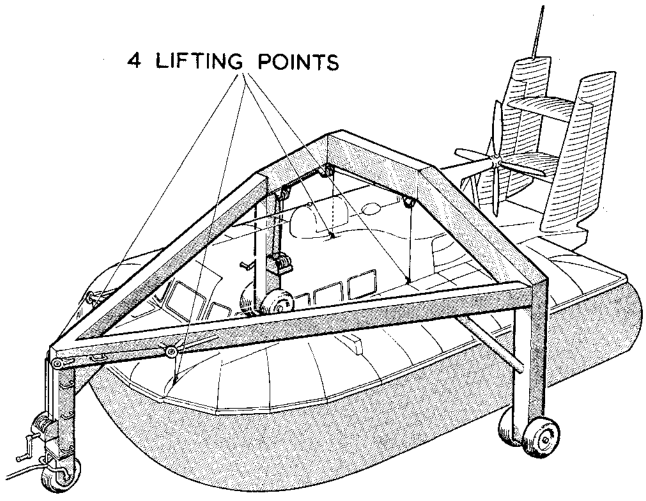

Fig. 18 SR.N5 lifting and handling gantry.

Figure 17 shows one unit of the three-unit chassis built for the SR.N2. This very much larger chassis was designed to take a load of 10 tons per unit and can be fitted with the aid of a mobile crane when the craft is on its landing pads. Hydraulic jacks, which form the top limb of the chassis, can then be extended bringing the axis vertical, thus lifting the craft 16 in. so that the skirts are resting only lightly on the ground.

Two main considerations have made us abandon this approach on subsequent machines. For craft with long skirts it becomes necessary to provide a greater lift of 4 ft or more; this poses difficult chassis and attachment design problems. When operating from nontidal waters, a chassis cannot be easily attached, since it must be fitted to a floating craft if it cannot be hovered ashore.

The proposed solution for the SR.N5 is a lifting and handling gantry of the type shown in Fig. 18. This is relatively cheap, provides full facilities for retrieving, handling, and skirt inspection and repair, and imposes an almost negligible weight penalty on the craft. The provision of additional jacking points at the fore and aft ends of the craft means that for long periods of work it can be jacked up and the gantry used elsewhere. It is believed that much the same solution has been adopted for the Bell Hydroskimmer, a considerably larger craft than the SR.N5, and as far as the writer can see, it will still be the most acceptable solution even for craft in the 150–250 ton class. Looking much further ahead, it is the 500–1000 ton size that poses the real problem.

In this case, there appears to be no alternative to the use of a dry dock equipped with gantries or cranes capable of lifting the heavy items of equipment. A sketch of such a dock is shown in Fig. 19. It could, of course, be fully enclosed in-

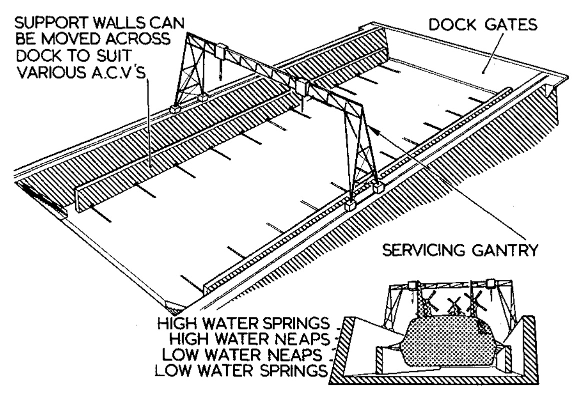

Fig. 19. Servicing dry dock for 500/1000 ton hovercraft.

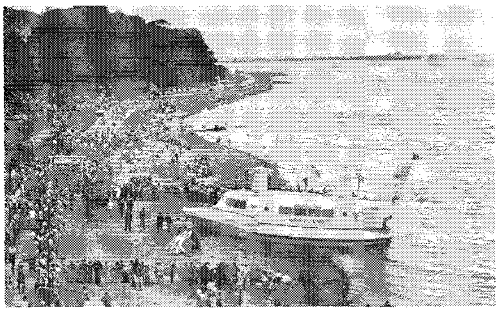

Fig. 20 Photograph of SR.N2 on beach at Ryde.

stead of being open to the weather. This would be very desirable if one were dealing with a nuclear powerplant and its associated equipment. The length and depth of the dock and its load-carrying capability need only be small compared with one for a ship of equivalent beam, and therefore it may not be so expensive as it might seem at first glance. It will be seen that it is suggested that variable support walls, which may be adjusted to suit the width of the craft, are provided to support the craft by means of temporary brackets fitted to the sides. By this means the craft would be suspended above the dock and clear access obtained to the bottom and skirts.

6.3. Terminal Requirements

Probably one of the greatest attractions of the hovercraft is that, unless it is designed solely for marine use as are certain sidewall craft, it is inherently amphibious. This is of great importance when opening up a route or for giving demonstrations where a "terminal" can consist of a small beach just large enough for the craft to nose on to, as for example in Fig. 20, where the SR.N2 is shown operating from the beach at Ryde in 1962. Passenger steps shown in Fig. 21 were hooked into place to load and unload. Turn-around times of 3 min were recorded handling forty passengers in each direction. Therefore, it can be seen that in its crudest form it is quite feasible to use any reasonably flat beach or bank, the minimum dimensions of which can be about as long as the craft and twice as wide. This surface is best given a covering of tarmac if used intensively and not "reset" by tidal conditions each day. Figure 22 shows the tarmac ramp laid at the Dorval Yacht Club for the Canadian demonstration, i.e., at a nontidal area.

Fig. 21 Photograph of SR.N2 passenger steps.

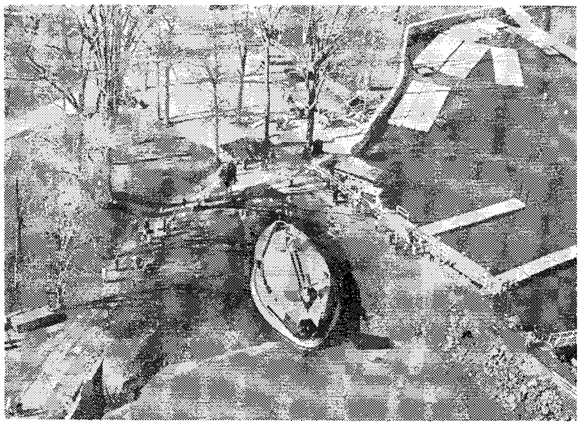

Fig. 22 Photograph of Tarmac ramp at Dorval.

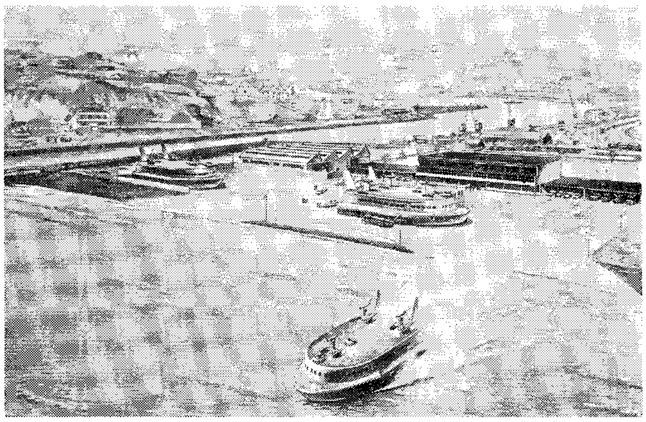

Fig. 23 Artist's impression of large hoverport.

However, for a regular passenger service with larger craft, a more elaborate base will be required, largely dictated by passenger and, in some cases, vehicle handling, facilities such as ticket offices, waiting rooms, refreshment rooms, car parks, and ramps, and, on international routes, customs offices. In all cases, it is considered that to cut down turn-around times the craft will be brought ashore probably up concave ramps. Two ramps set at roughly 90° to one another will give a good flow for normal operations and cater for serious cross-wind or rough-water conditions where only one or the other may be used. Figure 23 shows an artist's impression of a larger hoverport on these lines; obviously there are many alternative arrangements in between the two extremes shown in this and the two previous pictures.

One further possibility worth discussing is the use of pontoons such as the Storey "Uniflote" system for providing a dock where a service has to be connected with normal port or pier installations. This was studied for a possible SR.N2

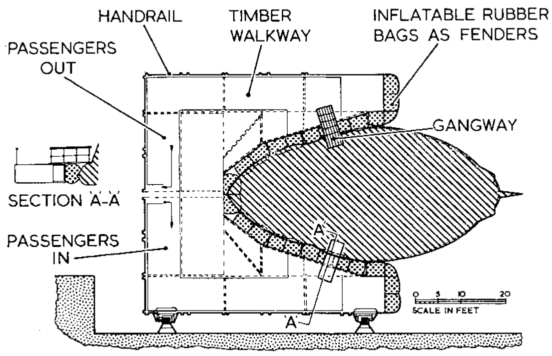

Fig. 24 Scheme for floating dock made from Storey "Uniflote" components.

service, and the arrangement is shown in Fig. 24. The U-shaped dock was to act as a loading platform and allowed the SR.N2 to dock rapidly at any state of the tide. This arrangement is, of course, very similar to the flying-boat dock, once a more familiar scene than it is now.

7. Conclusions

We hope that the operational results discussed in this paper have helped to show that the hovercraft (i.e., air-cushion vehicle) is already a very safe and comfortable vehicle which has been developed to the point where it is a suitable and competitive form of transport for relatively short, sheltered-water routes.

There also appears to be a significant place for the smaller, high-performance utility hovercraft for rescue, exploration, and out-back transport roles in the more undeveloped and barren areas of the world. For the first time we have a nonflying craft that can traverse grassland, ploughed fields, mud, sand, snow, and water with almost equal ease, providing the discontinuities are not too great.

For the opening up of an area we think we may well see vehicles operating over bulldozed tracks, these tracks possibly being slightly concave in section and devoid of trees, shrubs, and boulders. This will allow a simpler, cheaper craft to operate at quite nominal clearances (and if twin guide tracks or "single line" working is used, the risk of collision is avoided).

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Application of Flight Simulators to the Development of the A-5A Vigilante

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The development and use of flight simulators as an aid to solving many of the critical design problems encountered during the design and development of the A-5A Vigilante are briefly traced in this paper. Flight simulator studies, piloted and nonpiloted, played an important role in the development of the airplane. The early determination of roll coupling problems due to high spoiler-slot-deflector yawing and pitching moments and the subsequent correction of the problems through the incorporation of the inverted spoiler-slot-deflector system can be attributed to the use of flight simulation. In addition, it is shown that the criteria for determining satisfactory lateral-directional and longitudinal handling qualities established by piloted flight simulator studies are in good agreement with pilot opinion from flight test.

Nomenclature

b = wing span, ft
$C_{1/2}$ = cycles to damp to half amplitude, cycles
C_l = rolling moment coefficient
C_n = yawing moment coefficient
f_n = natural frequency, cps
Fs = stick force, lb
g = acceleration due to gravity, ft/sec²
I_x = roll inertia, slug-ft²
K = function of the period of an oscillation
L = roll acceleration, $qSbC_l/I_x$, deg/sec²
n = load factor, g
P = period of oscillation, sec
$|p_1|$ = amplitude of roll rate oscillation at first overshoot, deg/-sec
$|p_{ss}|$ = absolute value of steady-state roll rate, deg/sec
PR = pilot rating
q = dynamic pressure, psf
S = wing area, ft²
$T_{1/2}$ = time for oscillation to damp to half amplitude, sec
$|v_e|$ = amplitude of lateral equivalent velocity oscillation, fps
β = sideslip angle, deg
δ = appropriate cockpit control deflection, deg or in.
ζ = damping ratio of oscillatory mode
$|\phi|$ = amplitude of bank angle oscillation, deg
τ_p = roll mode time constant, sec

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Introduction

HANDLING-QUALITIES requirements for military aircraft provide invaluable guides in tailoring the design of piloted vehicles to meet the pilots' needs. However, with each advancement in vehicle design and each change in mission requirement there has been a corresponding new set of