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HMCS Bras D'Or—An Open Ocean Hydrofoil Ship

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Read in London at a meeting of the Royal Institution of Naval Architects on April 22, 1970, Mr. R. N. Newton, R.C.N.C. (Vice-President) in the Chair.

SUMMARY: HMCS BRAS D'OR is a 200 ton 50-60 knot hydrofoil ship designed for anti-submarine operations in the open ocean (Fig. 1). This paper outlines the hydrodynamic principles on which this novel design has been based, describes the main features of the ship and reports progress of initial trials. While her evaluation is far from complete, early results are promising and some preliminary thoughts are presented on prospects for this type of ship in both military and commercial roles.

1. INTRODUCTION

Program Origins

The problem of increasing the speed of ships in rough water has thwarted naval architects since the invention of the screw propeller. In this period, which has seen aeronautical development progress from the Wright brothers to Appollo 11, the maximum speed of ships has remained virtually unchanged. Essentially this is because of surface wave resistance and the compounding effects of the rough water surface. The lesson is simple. The bulky hull of a ship must be kept away from the surface to travel at high speeds.

As soon as the advent of nuclear power plants allowed reasonable divorce from the atmosphere, the submarine designer was quick to learn this lesson, and today's submarine is designed with hardly any concession to satisfactory operation on the surface. Such a vessel has a much higher speed potential than a conventional surface ship.

Operating a navy which specialises in anti-submarine warfare (ASW), the Canadian Forces have long been concerned with this potential, and in the early 1950's the Defence Research Board sought to reverse the imbalance. It was recognised that the hydrofoil principle provided the most promising approach to high rough-water speeds above the surface. Commercial hydrofoil ferries in Europe were already pointing the way but their speed and seakeeping ability were inadequate for ASW operations. The DRB project at Defence Research Establishment Atlantic (then named Naval Research Establishment) was directed toward the next generation of hydrofoil craft, with emphasis on all-weather operation in the open ocean.

In its early stages the project was based on the ladder system of hydrofoil support, which appeared most promising for rough-water operation in the 40-60 knot speed range appropriate to ASW. This system was originally developed by Alexander Graham Bell and F. W. Baldwin immediately after World War I on the Bras d'Or Lakes in Nova Scotia. A detailed account of this pioneering work has already been presented to the Institution by Crewe.(1) Concentration on the ladder system also allowed the Canadian project to complement research in the United States, which already appeared to be covering other promising systems.(2)

Development of the Bell-Baldwin system during the 1950's has been well documented by Crewe(1) and Eames(3) and requires no description here. By 1960 a broad understanding of design principles had been gained and the promise appeared to be realisable in the form of a craft sufficiently large to serve a meaningful role in ASW. Accordingly, the Canadian Forces embarked on a detailed design study, with the DeHavilland Aircraft of Canada Limited (DHC) as prime contractor, and subsequently on an ambitious program to build a developmental 200-ton hydrofoil ship, designated FHE-400. Details of the program have been presented to the Institution by Milman and Fisher,(4) and for the purpose of this paper it is only necessary to outline the original operational concept which governed the design of the ship.

DREA Operational Concept

The major problem of ASW is initial detection, reliable sonar ranges being very small compared with the vast area of ocean to be covered. A promising alternative to the direct approach of improving sonar range is to devise means of providing a significantly larger number of present-day sonars in an economical manner—the so-called 'small and many' concept. This has advantages in flexibility of deployment and relative invulnerability, and it calls for development of the carrying vehicle rather than of the sonar itself.

The basic requirements of ASW demand an extremely versatile vehicle. Initial detection calls for long endurance at slow search speeds; interception and attack require short bursts at speeds exceeding those of conventional ships. These needs have forced the development of vehicle combinations which possess some of the characteristics of both ships and aircraft such as destroyers carrying helicopters. In this respect the hydrofoil ship, which is indeed half ship and half aircraft, promises unique advantages.

Moreover, several hydrofoil craft of the type envisaged could be built and operated for the costs involved in a single helicopter-destroyer, exploiting the 'small and many' idea. The essential point is that the degree of stabilisation offered by the hydrofoil principle, both foilborne and hullborne, makes the hydrofoil craft by far the smallest surface vehicle potentially capable of sustained operation in the open ocean.

There is an important difference in the concept of an ASW hydrofoil ship, as compared with passenger ferries or other hydrofoil craft intended to proceed continuously at high speed from one harbour to another. Since the ASW craft can be

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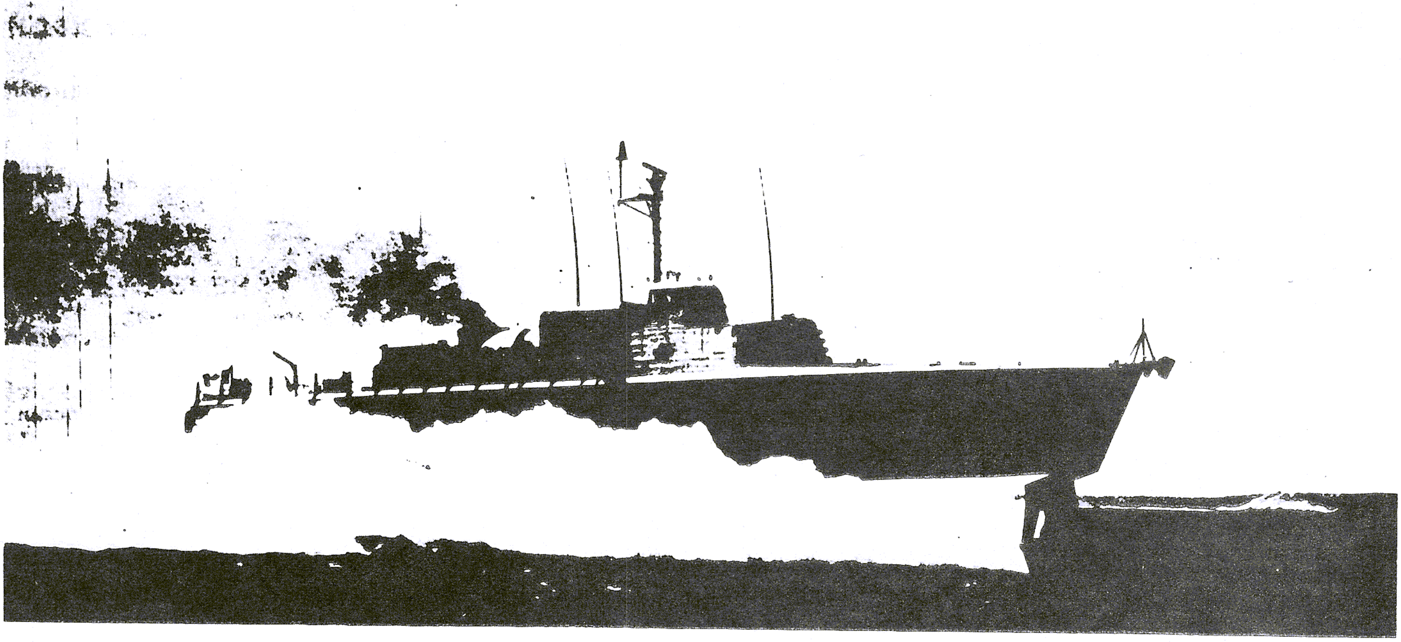


Fig. 1. HMCS BRAS D'OR at 62 knots (1969) (photo by W. R. Carty)

expected to spend most of its operating hours on search duties, hullborne operation at slow speed is at least as important as foilborne operation at high speed. Hullborne seakeeping, endurance and habitability are of much greater concern than in other hydrofoil applications.

Once a submarine has been detected, the advantages of high speed and a large number of small craft for interception are self-evident. For the kill, high speed must be coupled with manoeuvrability and good weapon payload. A high order of seakeeping and reliability are the primary requirements for foilborne strikes, rather than the attainment of extreme lift/drag ratio. Thus even in the foilborne mode the design priorities differ from those of the ferry-type of craft.

2. HYDROFOIL DESIGN PRINCIPLES

Having drawn attention to the relative importance of hullborne characteristics in the design of HMCS BRAS D'OR, it will now be assumed that this Institution requires no discussion of the principles of hull design. On the other hand, the basic ideas of hydrofoil design as applied to this ship are sufficiently novel to warrant an explanation which has to start from elementary principles. The resulting unbalanced presentation is deliberate and should not be misinterpreted.

Elementary Principles

Fully-Submerged Foils

A hydrofoil craft is essentially an aircraft with its wings operating under water, but the vertical limits within which the wings must be constrained to fly are too precise for the craft to be controlled like an aircraft. Some type of automatic altitude control is essential. There are two approaches, one based on controlling the lift coefficient by flap deflection or variable incidence, the other based on varying the immersed area, and each gives rise to a completely different type of craft.

The so-called 'fully-submerged' system, as employed in the U.S. hydrofoil development program, uses ultra-sonic sensors and gyroscopes to obtain continuous signals of altitude relative to the oncoming waves and craft attitude. These activate electro-hydraulic systems which control the deflection of flaps or the incidence of 'all-flying' elements of the foil system. This method of control is the most efficient in terms of minimum drag but it entails complete reliance on the electronic and hydraulic systems and on many moving mechanical parts under water.

Surface-Piercing Foils

In essence the contribution of the Bell-Baldwin team was to develop the alternative 'surface-piercing' system of altitude control, illustrated in Fig. 2. This shows DREA's first hydrofoil craft 'Massawippi' which now resides in the Maritime Museum at Halifax. Instead of controlling the angle-of-attack, fixed hydrofoils are so arranged that their immersed area

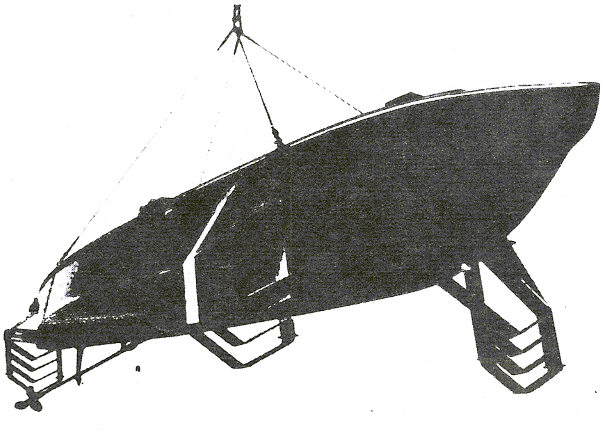


Fig. 2. Surface-piercing foil craft 'Massawippi'

varies with altitude, by using large dihedral angles or the ladder concept, or both as shown here. For any speed there is an equilibrium waterline where the weight of the craft is balanced by the lift of the foil area remaining submerged. Reserve foil area is available above water to become effective immediately the foil unit enters the face of a wave. Because the foil elements necessarily pierce the surface, a drag penalty is involved but, having no moving parts and no 'black boxes', the system is inherently simple and reliable.

The freedom that the designer has, to vary foil unit geometry with speed, permits the speed range between take-off and maximum to be significantly greater than with fully-submerged foils of constant area. However, the dynamic response in rough water has to be optimised at some speed, usually the maximum, and a large foilborne speed range can make it difficult to provide good response near take-off.

The Canadian program remains based on the surface-piercing system. It is thus fully complementary to the U.S. effort and the two programs cooperate closely.

Foil Unit Characteristics

Compared with the ideal two-dimensional aerofoil, a hydrofoil operating close to the water surface generates less lift. The water surface above the hydrofoil distorts to relieve part of the pressure drop on the upper surface, reducing the rate of change of lift with angle-of-attack well below the ideal value of 2π. There is a further reduction due to a similar pressure relief over the ends of a foil of finite span, corresponding to the aspect-ratio effect of aerodynamics. Both phenomena can be studied by vortex theory, and for a rectangular surface-piercing foil element, a simple approximation developed at DREA for the lift at speed V is

$$L = \tfrac{1}{2}\rho V^2 \left[c^2 \left(\frac{h}{c} + \frac{1}{2} \right) \cot \gamma \cos \gamma \right] 2\pi\alpha$$

with the angle-of-attack (α) measured in the vertical plane. The bracketed term is thus the 'effective area' of a surface-piercing foil, in terms of its chord (c), its dihedral (γ), and its depth of immersion (h). To a first approximation then, lift is a linear function of both angle-of-attack and immersion, and the partial derivatives $\partial L/\partial h$ and $\partial L/\partial \alpha$ can be regarded as constants for small disturbances about a steady-state condition.

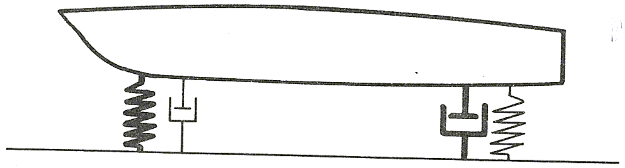
One can thus think of a surface-piercing foil unit as a damped vertical spring, with stiffness measured by $\partial L/\partial h$ and damping measured by $\partial L/\partial \alpha$, since vertical velocity is αV. With the product of these terms fixed by the static design requirement to produce a lift equal to craft weight, dynamic design is seen to be a process of proportioning the selected angle-of-attack and immersion depth to provide the optimum ratio of stiffness to damping for the unit. This is a greatly oversimplified statement but it enables a feel for the dynamic design problem to be developed.

Hydrofoil Configuration

Trim Stabilisation

Consider the longitudinal behaviour of a craft with foils developing equal steady-state lift at bow and stern, as required in the 'tandem' configuration which has its centre of gravity (C.G.) mid-way between the foils. If the dynamic characteristics of the foil units are also identical at bow and stern, as pictured in Fig. 3(A), then an external disturbance heaving the craft downward will cause equal increments of lift to be generated, and the response will be vertical without change of trim.

A. BELL - BALDWIN



B. DREA CONCEPT

Fig. 3. Analogue for longitudinal response

If the foil unit stiffness is greater at the stern, a downward displacement will generate more lift aft, and the craft will trim down by the bow. This will decrease the angle-of-attack of both foils, tending to cancel the lift response produced by increased immersion. Dynamically, this situation frequently leads to a porpoising type of instability, and is obviously undesirable.

Conversely, if the bow is stiffer than the stern, the craft will trim up as it is depressed, increasing the angle-of-attack and augmenting the lift response to increased immersion. In effect, the stiffer bow foil is adding some measure of incidence control to the surface-piercing system, but doing it without moving parts by using the trim of the whole craft.

DREA Foil System

As represented in Fig. 3(B), the essence of DREA's improvement on the basic Bell-Baldwin idea lies in this use of different foil characteristics at bow and stern to augment the surface-piercing effect and thus reduce the foil area or number of ladder rungs needed to obtain the required response. In this way the overall craft stiffness can be reduced and its damping increased, resulting in a much smoother ride in rough water and lower dynamic loads on the structure.

The advantage of this approach becomes more apparent when considering the craft entering the face of a large wave. The stiff bow foil responds to its increasing immersion and lifts, trimming the craft to a climbing attitude and increasing lift. Down the back of the wave the reverse action is similarly favourable. It is also desirable that the bow foil be reasonably insensitive to angle-of-attack variations caused by orbital velocities in the wave, otherwise it would not respond adequately in a following sea, the pitfall of all early surface-piercing designs. Thus the bow foil should be relatively lightly damped and this is consistent with its greater stiffness. There is a practical limit, of course. Too much stiffness and too little damping of the bow foil will cause excessive pitching motions and defeat the whole object of improving overall craft damping.

In general the efficiency of a foil unit, as measured by its overall lift/drag ratio, increases with $\partial L/\partial \alpha$, or damping, and decreases with $\partial L/\partial h$, or stiffness. Hence the DREA concept is calling for inefficient foil units at the bow and efficient foil units at the stern.

Longitudinal Configuration

In the light of this, DREA went astray at first in following too closely the Bell-Baldwin ideas and conventional aircraft practice. For example, DREA's second hydrofoil craft 'Baddeck' (originally named 'Bras d'Or') had three foil units of equal size, two forward and one aft, as shown in Fig. 4. Such a configuration is asking for two-thirds of the foil system to be inefficient. In the interests of achieving reasonable efficiency,

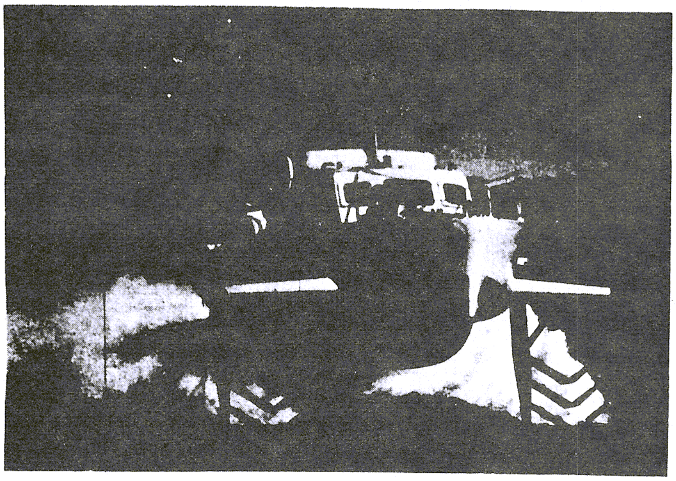


Fig. 4. Research craft 'Baddeck', ex. 'Bras d'Or'

inadequate stiffness was designed into the bow foils and poor longitudinal behaviour was the result. Indeed the stiffness was not even adequate for lateral stability. Incidentally, this fault has since been corrected and, with stiffer bow foil units, 'Baddeck' has been serving a very useful function for several years as a stable platform for high-speed towed-systems research and development.(5)

In comparison, the new foil system, conceived by DREA and developed by DHC for HMCS BRAS D'OR, calls for 90% of the weight to be supported by the main foils at the stern and only 10% to be carried on a small bow foil. It is shown in Fig. 5 in quarter-scale model form on DREA's research craft 'Rx'. Here 90% of the foil system can be efficiently designed, allowing the bow foil to be as inefficient as is necessary for good response. This tail-first or 'canard' configuration is essential to the DREA concept; it is the only way in which well damped motions and good performance in following seas can be combined with reasonable efficiency in a surface-piercing system.

Lateral Configuration

Turning to the question of lateral stability, craft which carry the majority of their weight on a main foil unit either at bow or stern, with a small auxiliary unit at the opposite end, normally have a much wider 'track' than tandem craft carrying 50% at the bow and 50% at the stern. Since the roll restoring moment varies as the square of the track, 90%-10% configurations have a distinct advantage.

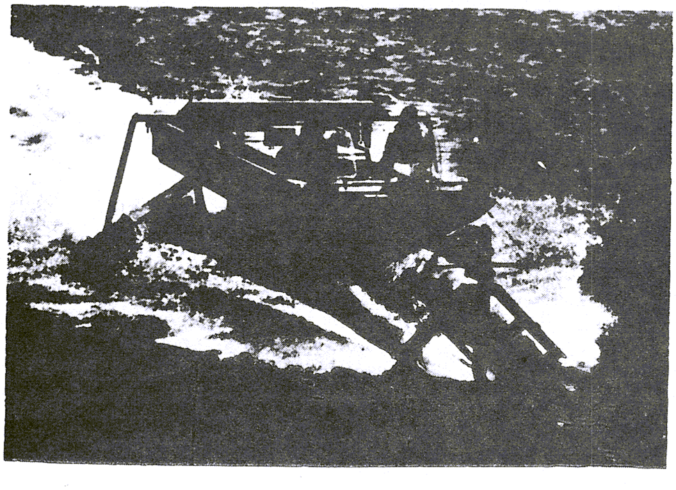


Fig. 5. Research craft 'Rx' with 1/4-scale FHE-400 hydrofoils

The prime requirement is for lateral stiffness and in the 'orthodox' aeroplane configuration with main foil forward, this follows naturally from the longitudinal requirement for greater stiffness at the bow. However, in the 'canard' configuration lateral and longitudinal requirements conflict, and this is probably the reason that most successful early hydrofoil craft were of orthodox configuration. Lateral stability is fundamental from the first moment of take-off in calm water; longitudinal characteristics are less demanding until one faces the problems of rough sea operation.

The DREA concept resolved this conflict by recognising that stiffness is required only at the ends of a wide main foil track. A completely submerged flat centre-section having no stiffness and very high damping, combined with surface-piercing side panels, can be made stiff in the lateral sense without detracting significantly from the overall characteristics required for longitudinal reponse. Fig. 6 illustrates the idea.

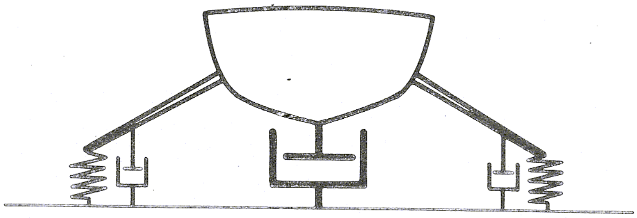


Fig. 6. Analogue of lateral response

This is not necessarily the only solution. Considerable controversy exists over the most desirable lateral configuration; whether or not the main foil should be split into two separate units, whether or not gyro-controlled flaps akin to the roll stabilisers of conventional ships should be added, and so on. Indeed, this paper has greatly oversimplified the whole question of hydrofoil configurations.

Seakeeping Ability

Platforming

The manner in which the two basic methods of altitude control respond to waves has been indicated, but it would be unsatisfactory if these worked exactly as outlined. This would mean that the craft would track the contour of all waves and excessive vertical accelerations would result.

A major potential advantage of the hydrofoil craft is that it is able to ignore seas which are much smaller than its hull-clearance and respond only to the higher and longer waves which incur lower vertical accelerations. If the craft is sufficiently large for its hull-clearance to exceed the maximum wave height for which it is intended, it should be designed to seek a mean altitude and maintain it regardless of the surface contour. This is known as 'platforming', and the U.S. type of fully-submerged control system has particular advantages in this regime.

Most short-stage passenger-ferry routes are in water sufficiently sheltered for platforming to be feasible a reasonable proportion of the time. However, in the open Atlantic craft exceeding 1,000 tons would be needed for true platforming.

Contouring

At the other end of the spectrum a very small boat must 'contour' up and down the slopes of large waves. In practice, open-ocean craft of the size of HMCS BRAS D'OR are designed for an intermediate response, ideally such that the hull just misses the crests and the foils just remain immersed at the troughs. These ideas are illustrated in Fig. 7.

It is for this intermediate regime, involving a fair degree of contouring, that the DREA concept has been developed, and the

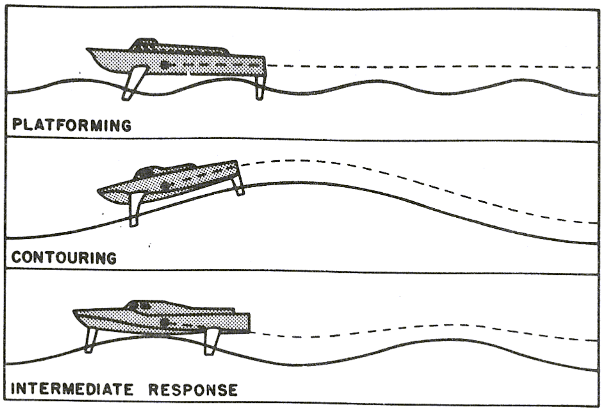


Fig. 7. Platforming and contouring modes

argument advanced for the canard configuration is largely based on the need to operate in waves higher than the feasible hull-clearance. The same argument does not apply to platforming craft or fully-submerged foil systems; for the U.S. types, satisfactory overall arrangements and craft performance can be achieved with either canard or orthodox configuration.(6)

Once some measure of contouring is accepted, the limit on seakeeping ability is set by the tolerance of the crew to the vertical accelerations thus caused. Here the standards set for the experienced crew of a naval vessel will differ from those which have to be imposed when the comfort of fare-paying passengers is at stake. Moreover the duration and purpose of a foilborne run are important factors. Quite severe 'seat-belt' conditions will be tolerated for short periods in the heat of a chase, but would be unacceptable for longer runs under more routine circumstances.

Wave height ceases to be a significant criterion in a contouring situation. Indeed in waves of constant steepness, the acceleration levels tend to decrease with increasing wave height. For practical purposes accelerations are virtually independent of wave height in waves larger than 1·5 times the hull-clearance, and wave steepness is then the governing parameter.

Minimum size for the open-ocean ASW role is thus determined by the degree of contouring which can be tolerated by the crew. Calculations based on a maximum wave steepness of 1 in 15 suggest that vertical accelerations will be acceptable at 50 knots head-on to a state 5 sea in craft which can be designed with a hull-clearance of 8 to 10 ft. This requires a minimum size of 150-200 tons. The upper limit of sea state 5 is critical for this size of ship; higher waves should result in easier motions.

Hullborne Behaviour

With a surface-piercing system, the take-off speed is low and the process is a continuous unloading of the hull. These features favour a relatively conventional high-speed displacement hull, rather than one of semi-planing type.

Accepting that the C.G. should be close to the main foil for good foilborne lateral stability. Fig. 8 shows the possible hull shapes, in somewhat exaggerated form. These are dictated by the buoyancy distribution needed to match the C.G. position, coupled with the fact that a contouring boat cannot have long lengths of hull overhanging the forward foils, as is done in some of the U.S. platforming craft.

Quite apart from the foilborne longitudinal response arguments presented earlier, the need for a hull shape optimising hullborne endurance and seakeeping, and the requirements imposed by sonar towing, clearly dictate the canard arrangement for the ASW role. There are many secondary advantages; the fine bow enables wave crests to be cut at high speed without pounding; heavy components such as machinery can be mounted close to the main point of support in a position encountering relatively low accelerations, thus leading to more efficient structural design of the hull, and generally the internal layout of the hull can be more satisfactorily arranged.

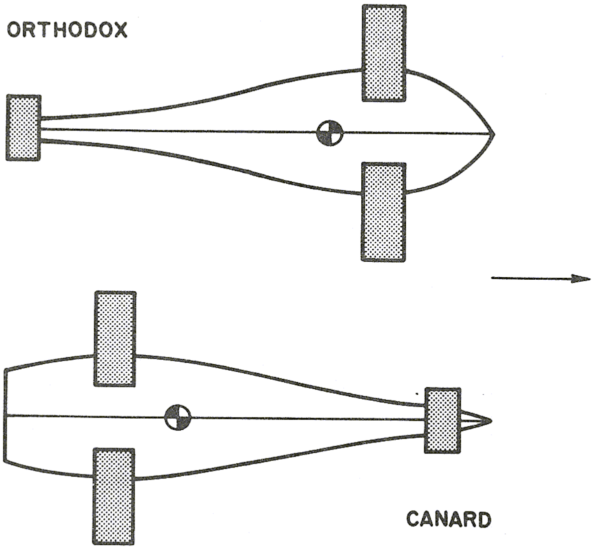


Fig. 8. Orthodox and canard configurations

Liveliness in ship motion is commonly associated with small size but low moments-of-inertia and light damping are the cause. In a conventional ship these characteristics are inherent in light weight and small size but in hydrofoil craft the foil units themselves develop very large damping and inertia forces, even when hove-to. On the basis of model tests and sea experience with DREA's small craft, a 200-ton surface-piercing hydrofoil craft should have motions at sea comparable to those of a conventional warship of about 3,000 tons.

For this reason the hydrofoils of HMCS BRAS D'OR have not been designed to retract. Berthing is not a problem in the envisaged role and the extra weight associated with retraction machinery and revised structural design is better allocated to payload.

Ventilation and Cavitation

Ventilation Inception

Since the upper surface of a hydrofoil is below atmospheric pressure at all useful speeds, it is susceptible to ventilation. If a suitable path exists, air will flood down the foil causing a drastic loss of lift. One of the remaining fundamental unknowns in hydrofoil research is exactly what constitutes a 'suitable path'.

On current evidence the main factor is that the flow must be separated over the full length of the path. When there is no separation at the water surface, it appears possible to sustain pressures so low that cavitation occurs before ventilation.(7) On the other hand, at very high angles-of-attack, when a foil is stalled and the flow is completely separated, ventilation occurs readily and no pressure drop can be sustained. The ventilated cavity then progresses smoothly down the foil as speed increases.

At realistic operating angles-of-attack there is a definite inception speed and a significant hysteresis effect. Inception is probably the result of a region of separated flow suddenly expanding to reach the surface, but the exact mechanism is not understood. A surface-piercing foil experiences no chord-wise pressure gradient along the waterline so that such a foil might operate with a large zone of separation below, but no separation over a narrow band at the surface. Under laboratory conditions this form of operation has been demonstrated but a minor local disturbance of the water surface, breaking this 'pressure seal', is enough to cause sudden ventilation of the entire separated zone. At sea, such disturbances would be present continuously and a 'pressure seal' is probably not the only mechanism of hysteresis.

Fencing

Ventilation can be controlled by the use of chordwise 'fences', which act as physical barriers to the passage of the air. The foils are then designed to tolerate ventilation down to the first fence below the surface. If a fence is submerged rapidly, air will be carried with it and ventilation below the fence will take a considerable time to shut off, again introducing a hysteresis effect which adds to the generally discontinuous nature of ventilation effects. In practice, design against ventilation is a process of trial positioning and shaping of fences, and there is a strong need for greater understanding of ventilation phenomena.

Subcavitation Regime

The danger of cavitation dictates different approaches to design, (a) well below cavitation speed, (b) in the range where cavitation can be suppressed and (c) well above cavitation speed. In effect, speed regimes exist analogous to the subsonic, transonic and supersonic regimes of aerodynamics; the inception of cavitation on hydrofoils and of shock-waves on aerofoils is governed by the same pressure considerations.(3)

Fig. 9 illustrates the type of foil sections used in the three regimes. With reasonable lift coefficients and section thicknesses, conventional low-speed aerofoils are satisfactory to about 40 knots. This explains why existing commercial hydrofoil ferries have been operating successfully in moderate seas for years, while higher-speed rougher-sea concepts have been embroiled in the problems of cavitation and response. Within the subcavitation regime, hydrodynamic, structural and propulsion problems are all considerably eased and the engineering generally can be an order less sophisticated.

Delayed-Cavitation Regime

Cavitation can be delayed to higher speeds by careful section design, following the principle of uniform pressure distribution familiar to propeller designers. This is analogous to delaying the occurence of local shock-waves on a wing approaching Mach 1, and uniform pressure sections have been developed for aircraft.(8) Unfortunately these aircraft sections develop large local pressure drops away from their design condition, and cavitation resistance is high over only a small range of angle-of-attack. In rough water a hydrofoil's angle-of-attack is constantly changing due to craft motions and wave orbital velocities. A more tolerant section is needed. The section must also be modified for the effect of the water surface, proximity of struts, and other features of foil unit geometry on the pressure distribution

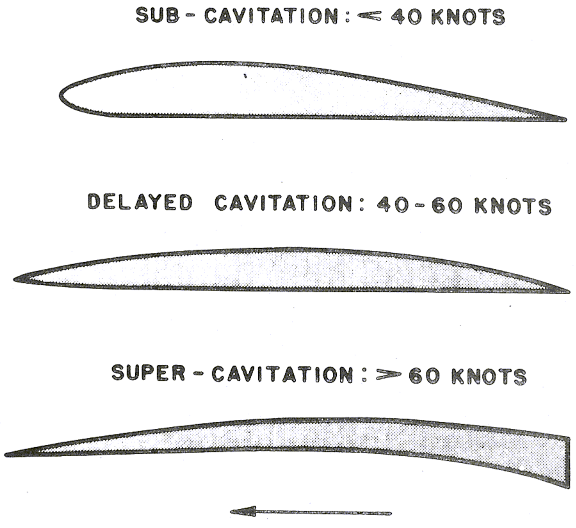


Fig. 9. Speed regimes and typical sections

Suitable sections have been designed(9) for cavitation free operation up to 60 knots in calm water, with good angle-of-attack tolerance for rough water operation at 50 knots. This is probably the practical limit of the delayed-cavitation regime. At higher speeds, lift coefficients are restricted to unrealistically low values and even at 60 knots the limit on section thickness causes very severe structural problems, demanding exotic materials and fabrication techniques.

The trend is seen in Fig. 10 which shows the cavitation characteristics of ogival foil sections in the form of critical cavitation number (σ_c) versus lift coefficient (C_L). As the required cavitation speed increases (cavitation number decreases) not only must thinner sections be used at lower lift coefficients, but the tolerance of the section to varying angle-of-attack also decreases.

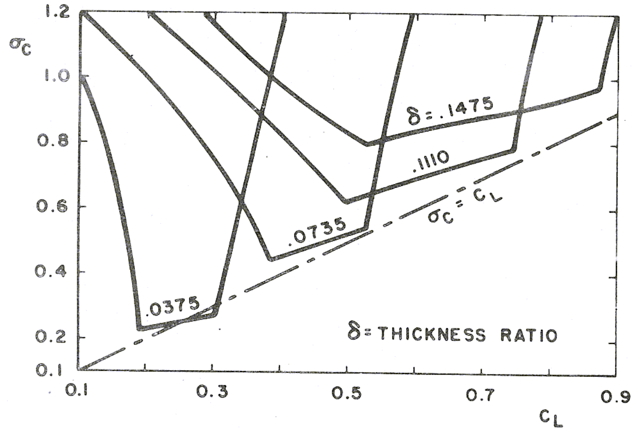


Fig. 10. Cavitation characteristics of ogival sections

Thus the range of lift variation available for incidence control decreases with increasing speed. It becomes difficult to provide control without employing changes of foil area, and this is the reason that the Bell-Baldwin system showed particular promise of seakeeping ability at high speed. The necessary lift variation increases with the degree of contouring demanded. For platforming craft, incidence or flap control is adequate well into the delayed-cavitation regime, as evidenced by the success of U.S. craft.

Comparison of σ_c-C_L characteristics for a large number of foil sections suggests that a first approximation to the practical limit of delayed-cavitation design is the broken line shown in Fig. 10, for which $\sigma_c = C_L$. This corresponds to a maximum hydrofoil loading of about 1 ton/sq. ft. for near surface foils.

Supercavitation Regime

When conditions make it impossible to avoid cavitation, the design philosophy is reversed. The objective then is to design a hydrofoil to maintain a continuous stable cavity. Although suitable for applications such as the blades of high-speed propellers, the true supercavitating hydrofoil is impractical for surface-piercing craft, because of the difficulty of maintaining a large cavity at vapour pressure close to the surface. The obvious modification is the superventilated hydrofoil,(10) based on the same principle but with the cavity open to the atmosphere. An air-filled cavity can be sustained at lower speeds, so that transition from wetted to superventilated flow can take place under conditions in which the resulting force discontinuity is not so serious.

In effect the superventilated foil is simply a planing surface of high efficiency but, cutting its own free surface, it is not in danger of pounding in rough water. The efficiency of this type of section can theoretically be as high as that of a conventional hydrofoil, but only at optimum angle-of-attack. Efficiency falls rapidly as angle-of-attack increases and, in practice, angles substantially beyond the optimum are needed to maintain a cavity that is sufficiently thick to contain a structurally feasible leading-edge, and to prevent cavity closure in rough water.

Under these high angle conditions the most exotic minimum drag designs do little better than simple arc forms, and the practical superventilated section has a very low efficiency. In general their practical use requires extensive further investigation.

Difficulty in designing delayed-cavitation sections having a wide enough range of angle-of-attack to accept the anticipated motions of a canard bow foil at high speed, led DHC to adopt these relatively unknown superventilated sections for HMCS BRAS D'OR's bow foil. This was an ambitious undertaking, involving extensive model tests and trials with the 'Rx' craft to develop a superventilated bow foil of satisfactory characteristics.

3. DESCRIPTION OF HMCS BRAS D'OR

HMCS BRAS D'OR is a 200-ton surface-piercing hydrofoil ship designed for anti-submarine operations in the open ocean. At a hullborne speed of 12 knots, her endurance and seakeeping ability should compare with those of a conventional destroyer-escort. Foilborne speeds up to 60 knots in calm water and 50 knots in rough water, with a range of several hundred miles, should provide a good speed advantage in tactical operations. The general arrangement and appearance of the ship are illustrated in Figs. 11 and 12 and leading particulars are given in Table I.

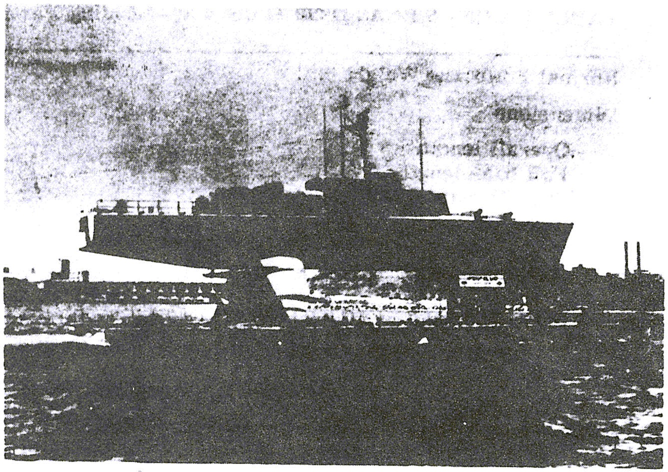


Fig. 12. BRAS D'OR on slave dock

Hull and General

General Arrangement

With the bow foil carrying only 10% of the ship weight, the C.G. is located well aft, providing a convenient arrangement for the main machinery and a good motional environment for weapons on the after deck. This arrangement is particularly well-suited to deployment of the variable depth sonar which will be an essential element of the ship's fighting equipment. The canard configuration allows launch and recovery to be carried out well clear of foils and propellers, and towing loads are absorbed by the comparatively large and insensitive main foil. The presence of the bow foil, on the other hand, makes it necessary to anchor the ship by the stern.

Hull shape was determined by the need for low hullborne resistance and wave impact loads. It is a slender displacement type of hull, with extremely fine lines forward and high deadrise. The clean design of the upper deck and superstructure forward helps to reduce air and spray resistance, a significant factor at maximum speed when winds over the deck can reach hurricane force.

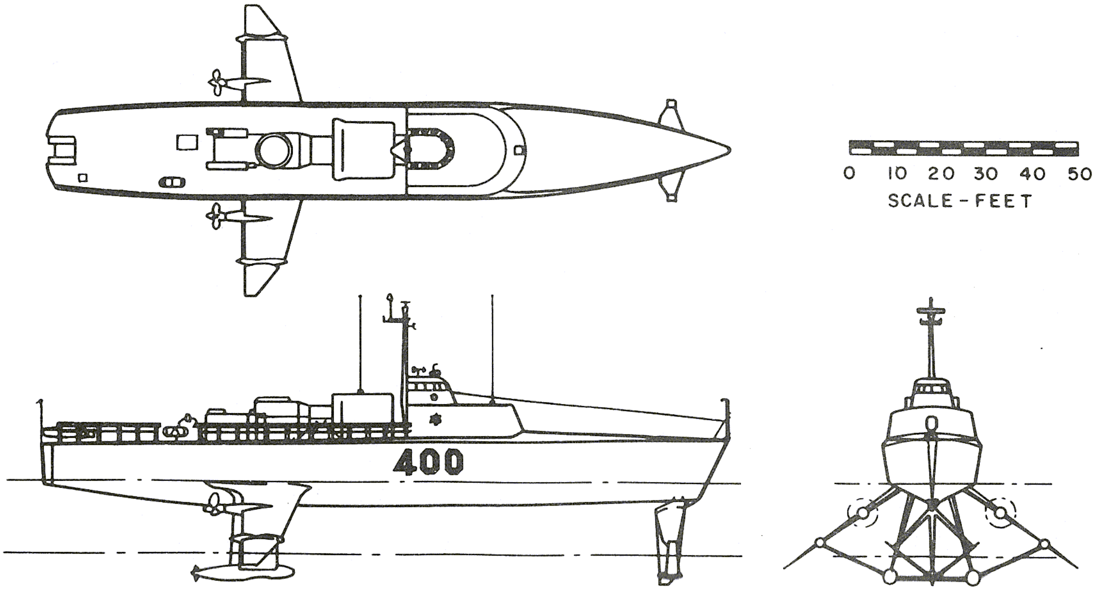


Fig. 11. BRAS D'OR—General arrangement

TABLE I HMCS BRAS D'OR (FHE-400)—Leading Particulars

Normal Foilborne Weight	475, 000 lb.	
Dimensions		
Overall length	150 ft. 9 in.	
Foil base length	90 ft.	
Overall main foil span	66 ft.	
Hull breadth	21 ft. 6 in.	
Overall height	47 ft. 0 in.	
Hull depth	15 ft. 7 in.	
Hullborne draft	23 ft. 6 in.	
Foilborne draft at 60 knots	7 ft. 6 in.	
Static freeboard	8 ft. aft, 11 ft. fwd.	
Hull clearance at 60 knots	10 ft. 6 in.	
Speed		
Maximum foilborne speed	60 knots (calm), 50 knots (rough)	
Design hullborne speed	12 knots	
Engines	Cont. Rating	Max. Rating
Foilborne: Pratt & Whitney FT4A-2 gas turbine	22, 000 shp	30, 000 shp
Hullborne: Paxman 16YJCM high speed diesel	2, 000 bhp	2, 400 bhp
Auxiliary: United Aircraft ST6A-53 gas turbine	390 shp	500 shp
Emergency: AiResearch GTCP-85-295 gas turbine	190 h.p.	—
Propellers		
Foilborne: two fixed pitch, supercavitating	Dia. 48 in. Max. 2, 000 rpm	
Hullborne: two KMW feathering, reversible pitch	Dia. 84 in. Max. 315 rpm	
Accommodation	Normal	Maximum
Officers	4	7
Petty Officers	4	6
Men	12	12

Hull Structure

The all-welded aluminum alloy hull is essentially longitudinally framed, but some departures from normal practice have been dictated by the importance of minimising weight, and by the concentrated nature of the loads when foilborne. Skin panels were prefabricated from extruded sections, butted together by machine-welding under controlled conditions to form comparatively large plates with integral stringers (typically 8 ft. × 40 ft.). This longitudinally stiffened shell, and similarly prefabricated deck, are welded to the outside of the transverse web frames and bulkheads, without any notching. Fig. 13 shows a cutaway view of the framing without the longitudinally stiffened shell.

D54S and 5083 aluminum alloy plate and extrusions are used throughout the hull and superstructure, except for the foil attachment fittings which are 7075(T3) forgings. Skin thicknesses vary from 0·25 in. on the bottom, to as little as 0·093 in. on the deck.

The hull was assembled upside-down to allow the maximum use of downhand welding. Transverse framing was erected on the completed upper deck and then the shell panels were welded in place. Hull construction was sub-contracted to Marine Industries Ltd., Sorel, Quebec.

Internal Layout

Internal arrangements are shown in Fig. 14. They are based on a normal crew of 20 officers and men working in two watches under cruising conditions and all accommodation is well insulated and roomy by warship standards. Abaft the narrow bow compartments, containing the bow foil steering and rake adjustment mechanisms, is washing and sleeping accommodation for 4 petty officers and 12 men. A small electronics bay separates the sleeping quarters from the galley and common dining-recreation area. The galley is designed to provide prepackaged meals for a 14-day period, being equipped with a large freezer and two microwave ovens. Conventional cooking facilities are also provided. Abaft the galley is the officers' accommodation comprising two single-berth and one double-berth cabin, plus a wardroom with spare berth-settees.

The main machinery space houses the hullborne diesel engine and its gearboxes, auxiliary and emergency gas turbines, foilborne transmission casings and fluid systems components. An electronics bay and workshop area is located abaft the main space, with VDS-well and towing-winch machinery installation at the stern.

The forward superstructure comprises the bridge and operations room, containing the fighting equipment, radio communications and engineer's control consoles. Superstructure construction is similar to that of the hull and is designed to resist wave impact. The layout of bridge controls, shown in Fig. 15, is reminiscent of an aircraft cockpit, with dual helm controls for the captain and coxswain and a navigator's jump-seat aft. Engine and propeller controls are provided both at the engineer's console in the operations room and on the bridge. The captain and coxswain manoeuvre the ship and apply power, but engine starting and auxiliary machinery control are handled from the engineer's console.

Abaft the bridge superstructure are the air intake and nacelle for the foilborne gas turbine. The upper deck is a natural location for this engine; it facilitates complete removal for maintenance, simplifies air and exhaust ducting and minimises transfer of noise and heat to the accommodation areas. The intake shell admits air to the engine through inlets facing aft and salt spray is removed by splitter-plates and by reversal of the air direction before entry to the engine bell-mouth.

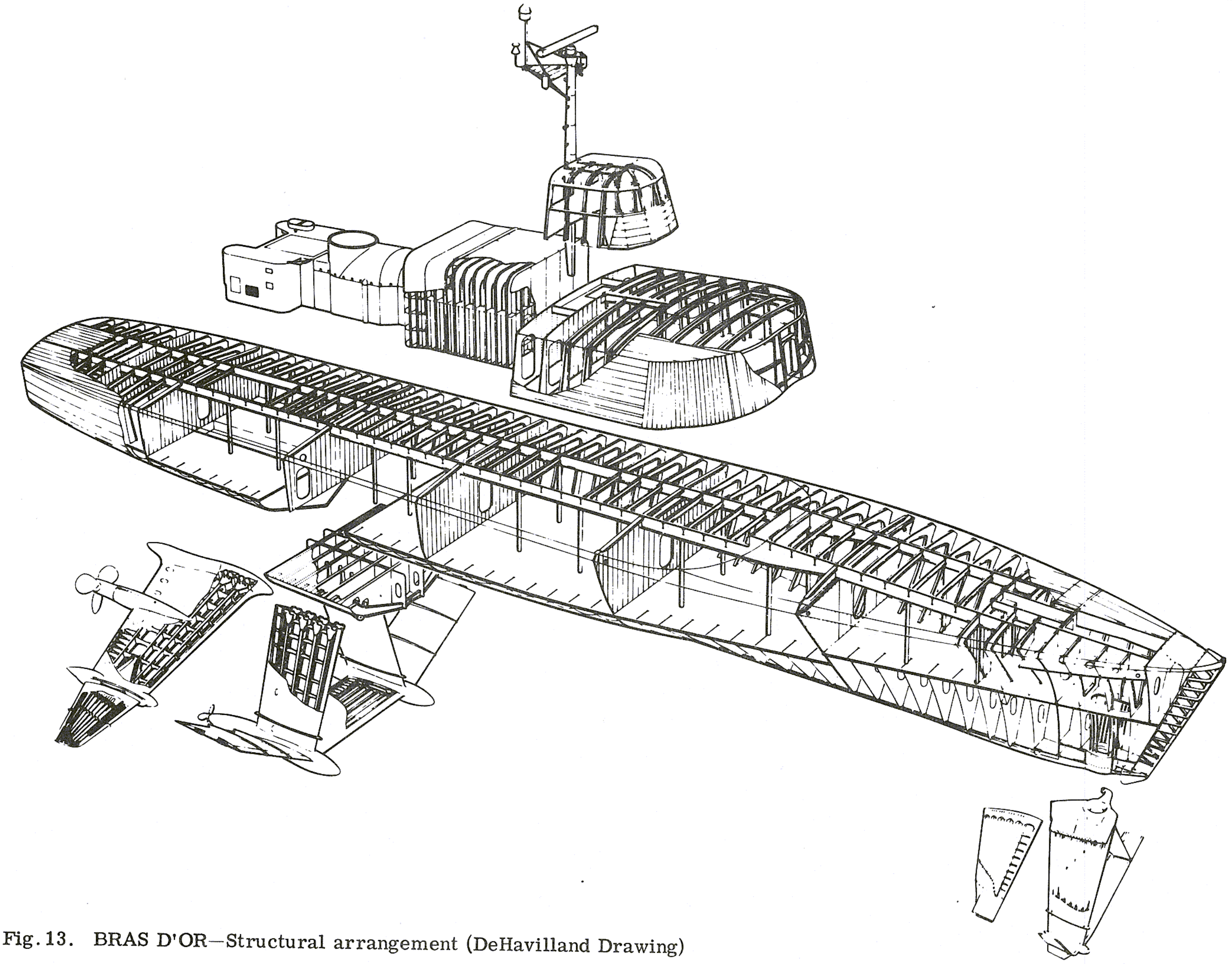


Fig. 13. BRAS D'OR—Structural arrangement (DeHavilland Drawing)

The aluminum alloy intake shell is lined with acoustic damping material which reduces noise transmission to the operations room and bridge to very acceptable levels.

Weight Breakdown

A weight breakdown for the ship is given in Table II, showing a disposable load which is 37·4% of the all-up-weight. This compares favourably with other hydrofoil craft and hovercraft and, particularly in light of the dual foilborne-hullborne requirement which enforces some duplication of systems, this reflects great credit on DHC engineering.

TABLE II Weight Breakdown

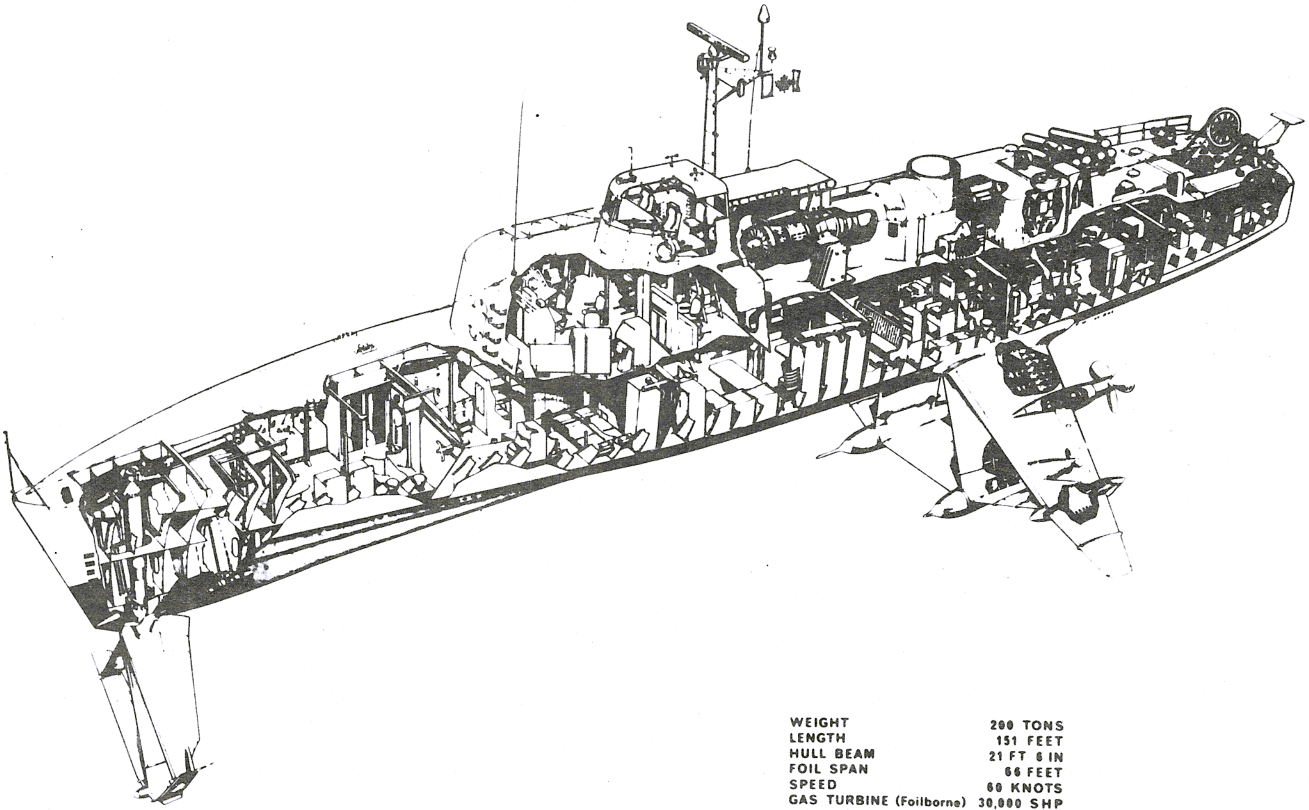
	Weight lb.	Percentage of 475, 000 lb.
Hull structure	73, 100	15·4
Foil structure	88, 300	18·6
Propulsion	77, 800	16·4
Systems and outfit	58, 200	12·2
Basic weight	297, 400	62·6
Fuel and payload	177, 600	37·4
All-up weight	475, 000	100·0

This is based on the maximum allowable weight for unrestricted foilborne operation, which is 475, 000 lb. Fuel or payload can be increased with some restrictions on the sea state for foilborne operation, while fuel stowage arrangements permit a substantial increase in all-up-weight for displacement operation only. Such overload conditions are particularly useful for cruising to a distant patrol area, allowing the ship to arrive with maximum normal fuel aboard.

Hydrofoil System

Hydrofoil Structure

The unusually large hull-clearance and high top speed cause limit load stresses in excess of 100, 000 psi in the foils, presenting very difficult structural design and fabrication problems. The foil elements are welded from 18% nickel maraging sheet steel and forgings. This is an expensive but very high strength steel having an ultimate tensile strength of 250, 000 psi. Major advantages are that this material requires only a low-temperature heat treatment without quenching and dimensional changes are small, reducing the problem of fabricating large foil structures to the close tolerances required. In common with other high strength steels in a marine environment, maraging steel is vulnerable to stress-corrosion cracking and hydrogen embrittlement, and the foil structure is protected by a neoprene coating. The foil skin varies in thickness up to 0·55 in. and typical internal structure is shown in Fig. 16 which illustrates the centre main foil. All foil leading-edges



WEIGHT	200 TONS
LENGTH	151 FEET
HULL BEAM	21 FT 6 IN
FOIL SPAN	66 FEET
SPEED	60 KNOTS
GAS TURBINE (Foilborne)	30,000 SHP
DIESEL (Hullborne)	2,400 BHP

Fig. 14. BRAS D'OR--Internal arrangement (DeHavilland Drawing)

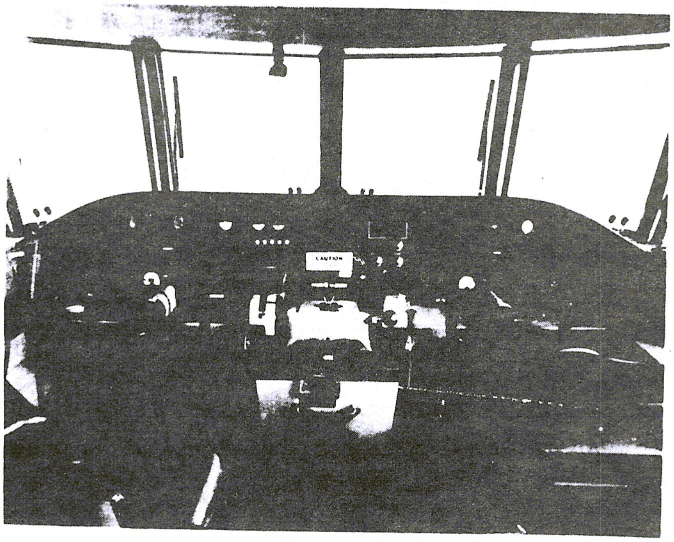


Fig. 15. Bridge controls

are replaceable, being external to the neoprene coating. They are made from stainless steel except those for the main anhedral foils which are plastic.

Bow Foil Unit

The bow foil unit shown in Fig. 17 uses superventilated sections with upper-surface spoilers to encourage and sustain ventilation over the widest possible ranges of angle-of-attack, immersion and speed. The low lift-curve-slope of these sections gives the bow foil unit the required characteristics of light damping and sensitivity to depth change, but it has a comparatively low lift/drag ratio.

The bow foil is steerable and acts as the rudder for both foilborne and displacement operation. It can also be adjusted in rake, enabling the best angle-of-attack to be selected for foilborne or hullborne operation under the prevailing load and sea conditions. Basically of diamond form, it has a vertical strut and short horizontal bridge-piece of delayed-cavitation section at the lower apex. The dihedral foils are pin-jointed to the bridge-piece and to the anhedral foils at the outboard intersections, but the upper ends of the anhedral foils are bolted rigidly to the strut. The mounting shaft pivots at a spherical bearing in the ship's forefoot and the upper bearing traverses through an arc to provide a rake angle adjustment of −15° to +5°, combined with a steering angle range of ±15° (restricted to ±5° for the foilborne mode). The steering actuator is located at the lower end of the bow foil shaft to avoid torsional oscillations and a yaw-rate gyroscope provides damping to smooth the steering. Steering can be controlled automatically from the ship's compass to maintain constant heading.

Main Foil Unit

The main foil unit, illustrated in Fig. 18, uses delayed-cavitation sections with fences to control ventilation. A central, fully-submerged, horizontal foil makes this a heavily damped and efficient unit and is supported by two nearly vertical struts. Outboard of these are intersecting dihedral and anhedral foil elements. The latter extend beyond the intersection and these anhedral tips are incidence-controlled in the manner of conventional ship stabilising fins.

This stability augmentation system was fitted primarily to meet a requirement introduced late in the design for extended cruising at low foilborne speeds. In practice, tip incidence control is likely to be used at all speeds to improve manoeuv-

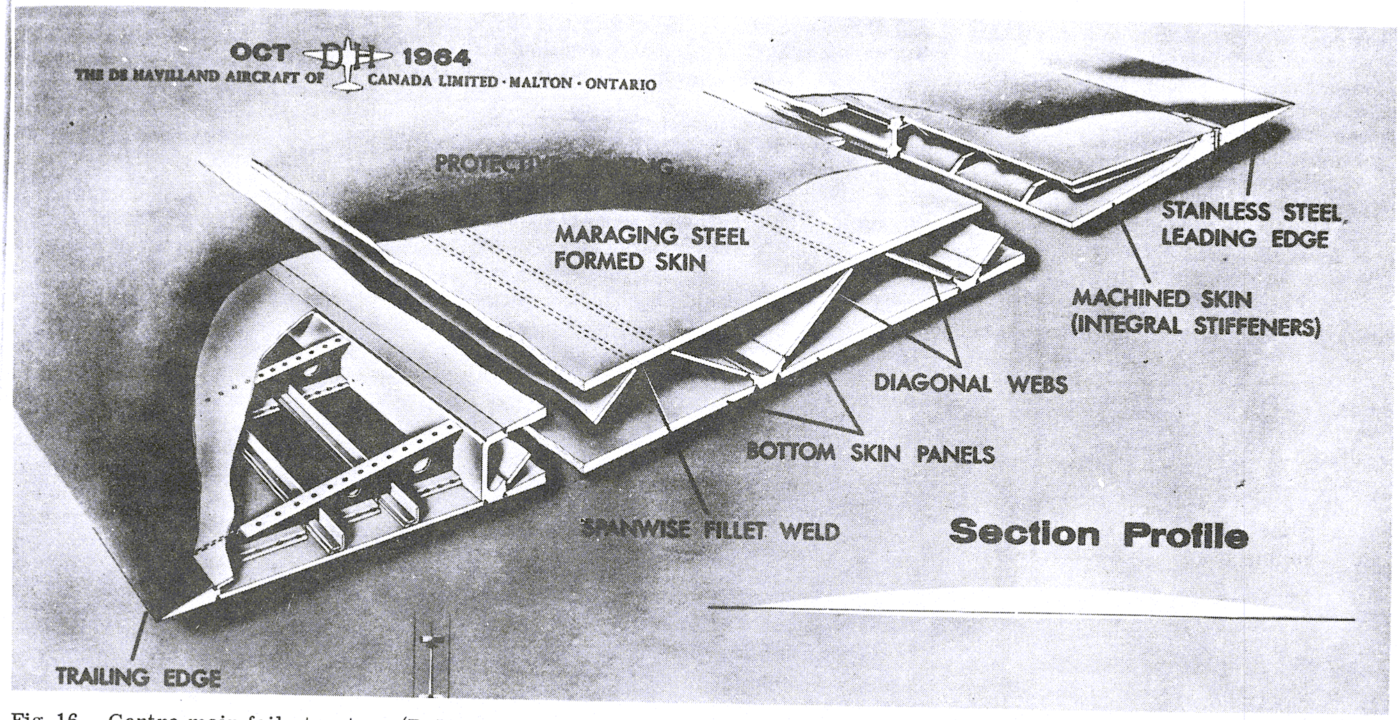


Fig. 16. Centre main foil structure (DeHavilland Drawing)

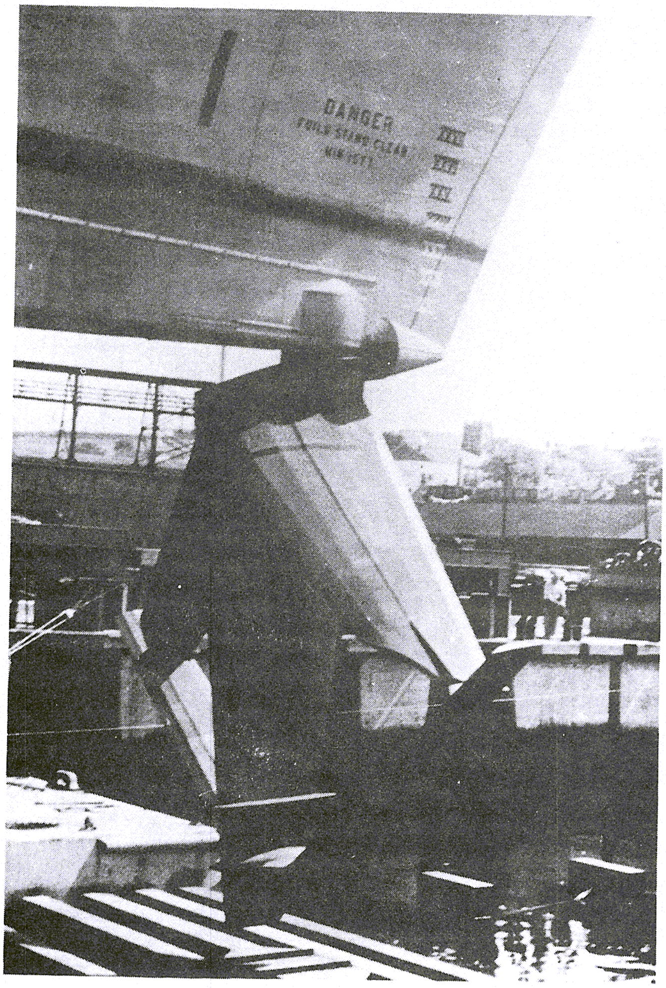


Fig. 17. Bow foil unit (DeHavilland Photo)

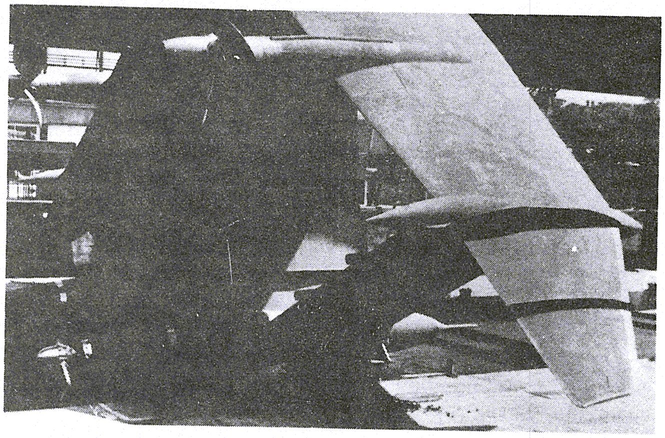


Fig. 18. Main foil unit (DeHavilland Photo)

rability. The tips are normally gyro-controlled but can be manually offset by a lever at the command position to allow coordinated or part-coordinated turns. The introduction of incidence-control, particularly at a late stage in the design process, posed formidable problems in the design and housing of actuators and in the structural design of the tip pivot arrangements.

The horizontal and dihedral foils are pin-jointed and each forged end-fitting of the anhedral foils and struts is bolted to the hull foundation by 16 bolts. The pods at the foot of the struts accommodate the outboard sections of the foilborne transmission and are 'waisted' to smooth the pressure distribution and prevent cavitation.

Machinery and Systems

Hullborne Machinery

The radically different requirements for hullborne cruising and foilborne operations dictate separate propulsion systems, as illustrated in Fig. 19. For the low-power long-endurance

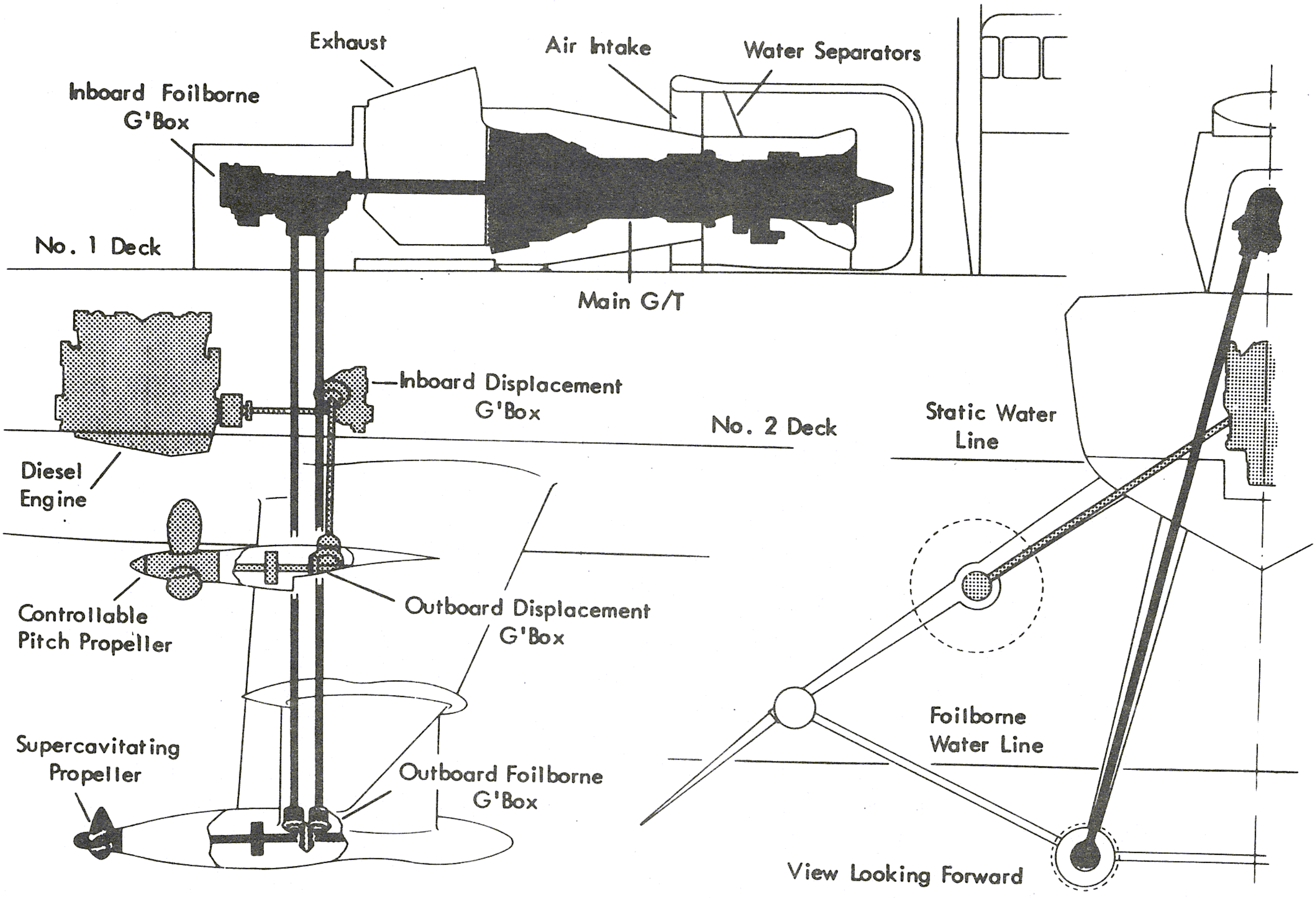


Fig. 19. Propulsion systems arrangement (DeHavilland Drawing)

hullborne system, fuel weight is the critical factor and a high-speed diesel engine is the logical choice. The hullborne engine is a Paxman 16 YJCM diesel with a continuous rating of 2,000 bhp at 1,500 rpm, driving two three-bladed propellers on pods mounted on the main anhedral foils. A central inboard gear-box drives bevel gears in the pods through shafts mounted within the anhedral foils. A remotely-controlled air clutch is installed in each downshaft. Both this and the foilborne transmission were designed and built by the General Electric Company of Lynn, Massachusetts.

The hullborne propellers have a diameter of 84 in. and were designed by Karlstads Mekaniska Werkstad of Sweden. They are fully-reversible, controllable-pitch propellers, with automatic pitch control provided by an oleo-pneumatic link with the diesel engine governor. The variable-pitch mechanism allows the propellers to be feathered for foilborne operation and their 30 ft. lateral spacing provides excellent manoeuvrability at low speeds using differential pitch control.

Foilborne Machinery

The high power required at maximum speed demands the use of a light aircraft-type gas turbine, specific engine weight being more critical than fuel consumption for the short periods of use. The foilborne engine is a Pratt and Whitney FT4A-2 gas turbine continuously rated at 22,000 shp at 3,600 rpm. Power transmission was difficult because of the very thin struts necessary to avoid ventilation and cavitation. Apart from the lack of internal space, these struts deflect appreciably under load, considerably complicating downshaft and bearing support design. Downshaft diameter was reduced by employing dual shafts geared up 1:2. The pod-mounted gear-boxes then provide a 4:1 down-ratio to the foilborne propellers, giving a net 2:1 reduction from the engine. The fixed pitch, three-bladed supercavitating propellers, 48 in. in diameter, were jointly designed by DHC and the Ship Division of the National Physical Laboratory. They are allowed to windmill for hullborne operation by means of an overrunning clutch.

Pressure lubrication is provided to the three hullborne gear-boxes and associated shafting using hydraulically driven pressure and scavenge pumps. Continuous wet-down is supplied to one system when the other is in operation. The oil is preheated before operation and cooled by sea-water heat exchangers when in operation.

Auxiliary Systems

The ship's electrical and hydraulic supply systems are provided through an auxiliary gear-box. For normal hullborne operation this is driven from the diesel engine, and for normal foilborne operation from a United Aircraft ST6A-53 gas turbine, continuously rated at 390 shp at 2,100 rpm. The gear-box drives three 60 KVA generators for the main 115/200 volt, 3 phase, 400 Hz electrical supply, six hydraulic pumps for the 3,000 psi main hydraulic system and a sea-water pump. An interesting feature of the auxiliary gear-box is that it can couple the auxiliary gas turbine to the inboard displacement gear-box to boost the diesel power or, in an emergency, for the auxiliary gas turbine alone to provide low-speed hullborne propulsion.

An AiResearch GTCP-85-295 gas turbine of 190 h.p. is available for emergency electrical and hydraulic supplies and to drive a sea-water pump. It is suspended from the deck beams in the machinery compartment, above the flooding line. Under routine conditions this emergency unit supplies starting air for the main gas turbine, conserving the pneumatic system reservoirs.

A common fuel is used by all three gas turbines and the diesel engine, providing complete flexibility of operations. JP-5 turbine fuel is normally used but high-distillate marine diesel oil is also satisfactory. The fuel is stored in four compartments below the lower deck and comprehensive inter-tank transfer arrangements are provided.

The main hydraulic system uses four continuous-duty pumps and four peak-duty pumps to supply 90 and 75 U.S. gallons per minute respectively to various hydraulic services. These include bow foil steering and rake angle adjustment, incidence control of the anhedral tips, an anchor windlass and powered bollard, the towed sonar winch and handling gear, air compressors for the ship's pneumatic system and pumps for the transmission lubrication system. Pneumatic services are supplied through reducing valves from high pressure reservoirs for weapon discharge, main gas turbine starting, diesel engine prime and start, hullborne transmission clutches, propeller automatic pitch-control and other miscellaneous duties. Salt water is distributed from a sea chest filled through inlets on the hull and foil structure, to various heat exchangers, the fire main and domestic services, and to a distillation unit for fresh water supply.

Operational equipment

Fighting Equipment

The Canadian Forces' aim has been to design HMCS BRAS D'OR as a complete ASW system and development of a special suit of fighting equipment has proceeded in parallel with ship design and construction. Basically this comprises a lightweight towed sonar for search and homing torpedoes for attack, with an integrated complex of navigation, radar, fire-control and communication equipment. The operations room complex and associated electronics have been assembled and are currently in use at the Canadian Forces Maritime Warfare School.

Because of the extremely small crew and the speed at which events will develop during foilborne interception, conventional operations room procedures and displays are inadequate. An automated Action Information System based on a digital computer has accounted for a major part of the development effort. Such a system offers advantages to naval ships other than hydrofoil craft, and while the AIS is perhaps the best example, there are many other areas in which naval ship design stands to benefit from the experience of new techniques forced by the special requirements of the hydrofoil.

The program now authorised stops short of installation of the fighting equipment suit. The intention is to conduct a thorough evaluation of BRAS D'OR as a sea going vehicle before making the decision whether to proceed to the second phase of evaluating the ASW system concept. Apart from economic considerations, this procedure maintains the proper perspective on trials objectives, and permits more extensive ship trials instrumentation to be carried than space would otherwise allow.

Currently therefore, a number of concrete blocks positioned to achieve the correct final C.G. location constitutes the ship's 'solid state' fighting equipment.

Trials Instrumentation

A comprehensive trials instrumentation system has been fitted in the operations room for the initial phases of ship trials, to record basic ship motion and performance characteristics and for measuring vibrations and strains in the hull and foils. In addition, a wide variety of propulsion and auxiliary system measurements can be transferred to oscillograph or tape recorders for detailed monitoring and analysis. This is accomplished through a central signal-conditioning and patch-panel installation which allows transducers throughout the ship to be interconnected with the recording equipment. A direct-reading 50 channel light-beam oscillograph is used for data requiring immediate monitoring and a 50 channel closed-magazine oscillograph is used mainly for strain measurements. A wide-band frequency-modulated tape recorder records vibration data in groups of six channels and a second tape recorder is used with a frequency multiplexing system to record up to 48 lower-frequency data channels.

Extensive use is made of photographic methods. The engineer's console is photographed automatically at rates up to 2 frames per second during trials and a special trials photo panel, equipped with precision gauges, records diesel and gas turbine engine performance. Cine-cameras photograph the flow over the bow and main foils in detail for short periods. A closed-circuit television system, including video-recording, displays the foils and the view ahead continuously in the operations room.

Comparison With U.S. Craft

HIGHPOINT (PCH-1) and PLAINVIEW (AGEH-1)

It is of interest to compare the 212 ton BRAS D'OR with the two large USN hydrofoil craft, the 120 ton HIGHPOINT and the 320 ton PLAINVIEW, described by Lacey(2) and more recently by Ellsworth.(6) A visual comparison is provided by the scaled profiles shown in Fig. 20 and Table III lists principal characteristics, following Ellsworth.

HIGHPOINT employs a fully-submerged canard configuration with 70% of the load on the high aspect-ratio main foil. Altitude is controlled by flaps on the forward foil commanded by ultra-sonic sensors at the bow. Pitch is similarly controlled by flaps on the central bay of the main foil, and roll by differential flaps on the outer bays of the main foil. Foilborne steering is by a flap on the bow foil strut, which also extends below the bow foil in the form of a spade rudder. Hullborne steering is by rotation of the 'outboard' drive unit, which also retracts behind the transom when foilborne. Each of the two

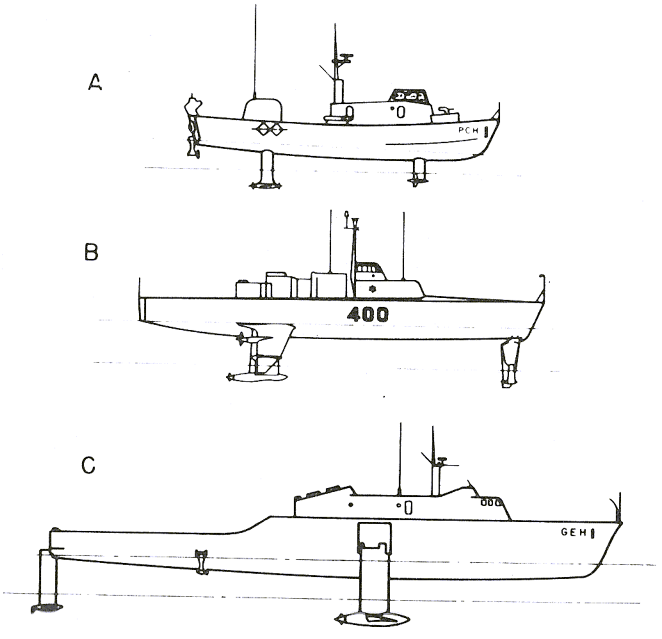


Fig. 20. A. HIGHPOINT (PCH-1) B. BRAS D'OR (FHE-400)
C. PLAINVIEW (AGEH-1)

TABLE III Comparison with U.S. craft

Characteristics	HIGHPOINT PCH-1	BRAS D'OR FHE-400	PLAINVIEW AGEH-1
Type	Fully-Submerged	Surface-Piercing	Fully-Submerged
Configuration	Canard	Canard	Airplane
Length Overall—Ft.	115·7	150·75	212
Beam Overall—Foils down—Ft.	33·3	66	70·8
Hullborne Draft—Foils up—Ft.	6·5	—	6·4
Hullborne Draft—Foils down—Ft.	17	23·5	25
Full Load Displacement—Tons	120	212	320
Hullborne Propulsion			
Engine	(1) Packard Diesel	(1) Paxman Diesel	(2) GM Diesels
Shaft Horsepower (cont.—total)	600	2000	1200
Thrust Producer	(1) 3-bladed Subcav. Prop.	(2) 3-bladed Subcav. Props.	(2) 5-bladed Subcav. Props.
Foilborne Propulsion			
Engine	(2) Bristol Proteus G.T.	(1) P & W FT4A-2 G.T.	(2) GM LM-1500 G.T.
Shaft Horsepower (cont.—total)	6200	22, 000	28, 000
Thrust Producer	(4) 3-bladed Subcav. Props.	(2) 3-bladed Supercav. Props.	(2) 4-bladed Supercav. Props.
Max. Hullborne Speed, Knots	12	12+	15
Calm Water Takeoff Speed, Knots	27	22	33
Max. Foilborne Speed, Knots	40+	50-60	45+
Foil & Strut Material	HY 80 Steel	18 Ni Marag. St.	HY 80/100 Steel
Hull Material	5456 Al.	5083 Al.	5456 Al.
Type of Control	Flaps	Tip assist	Incidence

Proteus gas turbines drives two conventional propellers, one on each end of the two main foil/strut intersection pods. The foils partly retract, moving vertically to stow close beneath the keel for reduced hullborne draft.

PLAINVIEW also uses fully-submerged foils, but in an aeroplane configuration with long bow overhang. Two separate main foils are used, with swept-back 'arrowhead' planform of moderate aspect-ratio. The stern foil is similar but smaller, and this whole unit is steerable. The incidence angle of all three foils is controlled in response to ultra-sonic sensors at bow and stern. Each LM-1500 gas turbine drives a four-bladed supercavitating propeller on a main foil pod. Hullborne propulsion comprises two retractable 'outboard' drives mounted at the quarters. All foils are fully retractable, the main foil struts swinging up in the roll plane and the stern unit in the pitch plane.

Intended Function

Most points of difference between the U.S. and Canadian concepts stem from the intended use of the craft. The Canadian FHE-400, albeit highly experimental, was designed as close to an operational prototype as current knowledge allowed. A follow-on ship need differ only to exploit the lessons learned from design and operational experience; the basic size and type are believed right for Canadian needs.

On the other hand, both USN craft are essentially research ships, although designed to explore operational capabilities. They are being used to obtain data for the subsequent design of prototypes in the 100-500 ton size range, but decisions on size and role are unlikely to be made before the operational potential of the research ships has been fully evaluated.

This does not apply to the smaller US craft FLAGSTAFF (PGH-1) and TUCUMCARI (PGH-2) which are 58 ton gunboats. These are not considered developmental and will serve as operational units of the fleet.(6)

Foilborne Operation

In keeping with the requirements of the 'small and many' ASW concept, the Canadian design emphasises seakeeping and reliability at the expense of foilborne efficiency, exemplified by the choice of surface-piercing system. One feature of this system well illustrated in Table III is the lower take-off speed made possible by the reserve foil area. Combined with the higher top speed, it gives a range of foilborne speeds more than twice that of the U.S. craft.

The configuration of AGEH-1 is clearly based on the platforming principle. Only a small degree of contouring could be tolerated before the long overhanging bow becomes immersed, introducing a danger of broaching-to.

Hullborne Operation

Probably the most significant difference is the importance attached to hullborne behaviour in the design of FHE-400. The hullborne mode is clearly secondary in the U.S. craft, as is appropriate to their hydrofoil research function. There were original statements that the foils of the USN craft would be retracted at hullborne speeds to reduce drag, presumably thinking of calm water operation in harbours where retraction is undoubtedly a navigational advantage. Later reports acknowledge the stabilising influence of extended foils, but there would seem to be inadequate hullborne power to maintain the quoted speeds in severe weather.

These three craft together embrace a wide range of design features and philosophy. Their evaluation in the open ocean should present a clear picture of their relative merits and provide the future designer with a sound basis for selecting the design characteristics best suiting his particular application.

4. MODEL AND FULL-SCALE TRIALS

The hydrodynamic design of the ship has been developed through extensive model tests and simulation studies. Model trials were carried out mainly at the National Physical Laboratory and the Admiralty Research Laboratory in England and the Defence Research Establishment Atlantic and National Research Council in Canada. A series of fourteen models of eight different sizes was used, from $^1/_{25}$ to $^1/_4$-scale. Table IV lists the major model test series and their principal objectives. Full-scale pre-acceptance trials are now under way at Halifax.

Laboratory Model Tests

Hullborne Behaviour

Hullborne characteristics were determined primarily from tests on a $^1/_{16}$-scale model at NPL. Resistance measurements were made in calm water and sea state 5, with and without hydrofoils. The hydrofoils account for up to 60% of the total resistance in calm water but the increment in total resistance due to operation in head seas is only about 20%. This is small compared with increments displayed by conventional ships, due to the massive damping effect of the hydrofoils which greatly reduces hull motions. Under typical open-ocean conditions, it would therefore seem that the ship will pay little or no penalty for the fixed hydrofoils in hullborne operation. Hullborne seakeeping tests were encouraging and, in particular, a $^1/_{25}$-scale model of the ship was shown to compare well with an equivalent model of a 5,000 ton conventional warship, hove-to in sea state 6-7.

Hydrofoil System

Main foil performance was assessed mainly from a series of $^1/_8$-scale model tests made at NPL between 1962 and 1965. These measured lift and drag characteristics, foil and pod pressure distributions, rolling and pitching moments and yaw characteristics.

The most extensive series of model tests was made on the novel superventilated bow foil, mainly at $^1/_4$-scale. This was the largest practical size for tank testing and it was also suitable for fitting on DREA's 'Rx' craft so that comparative open-water tests could be made. This large model size was thought to give good representation of ventilation effects, which basically follow Froude scaling. However, the influence of incorrectly scaled cavitation conditions on ventilation inception, persistence and cavity extent were unknown.

Consequently a $^1/_4$-scale bow foil model was tested at two different facilities; at NPL to obtain comprehensive performance data with Froude scaling, and at the variable pressure tank of the Lockheed Underwater Missile Facility, California,

TABLE IV FHE-400 Model Trials Summary

Model	Scale	Test Facility	Objective
Hydrofoil Ship	$^1/_{25}$	SIT, Hoboken	Hullborne performance and seakeeping
	$^1/_{16}$	NPL, Feltham	Hullborne performance and seakeeping
	$^1/_{16}$	NRC, Ottawa	Hullborne performance
Main Foil, Early Bow Foil, Coupled System	$^1/_8$	NPL, Feltham	Foil and pod pressure distributions, force and moment data, foilborne stability and response
2-D Sections of bow and main foil	$^1/_{12}$	ARL, Teddington	Force and moment data for attached and separated flow
Final superventilating bow foil design	$^1/_4$	NPL, Feltham Lockheed, Sunnyvale	Force and moment data Force and moment data for combined Froude and cavitation scaling
Bow foil elastic model	$^1/_6$	NPL, Feltham	Hydroelastic characteristics, force and moment data
'Rx' craft	$^1/_4$	DREA, Dartmouth	Foilborne stability, control and seakeeping in rough water
Variable pitch propeller	$^1/_8$	KMW, Sweden NRC, Ottawa	Verify propeller characteristics
Supercavitating propeller	$^1/_2$ & $^1/_4$	NPL, Feltham	Design, development and propeller characteristic predictions

to identify cavitation scaling effects by using combined Froude and cavitation number scaling. Flow observations and lift data showed no systematic variation with cavitation number and the scant full-scale data obtained to date tends to confirm this.

Supercavitating Propellers

Forewarned by an early history of blade failure, DHC approached the design of supercavitating propellers from the structural viewpoint. Initial tests on strain-gauged blades were aimed at optimising the sweepback angle and the spanwise distribution of blade-section centroids for minimum stress. Wake variations due to the main foil ahead of the propellers were measured by NPL and the expected harmonic frequencies checked against the results of blade vibration tests.

All models tested in the tunnel at NPL were 10 in. diameter and early models were of a 44 in. diameter propeller which did not develop the required thrust. Later models of the 48 in. diameter propeller eventually fitted met the thrust requirement and were felt to be capable of further development had time allowed. A detailed account of this propeller development has recently been presented by English and Davis.(11)

Simulation Studies

The basis for full-scale ship-motion predictions was a thoroughly comprehensive computer simulation which has been described by Davis and Oates.(12) Particular attention was given to lateral-directional stability for development of the variable incidence and yaw-damping control systems and to predict turning performance. The dynamic simulation studies also provided data for hydrodynamic loads, foil structure fatigue-life predictions, and habitability characteristics.

A very large analog computer was required to set up the six non-linear equations of motion and the random seaway input, including effects of orbital wave velocities, cavitation, ventilation and virtual inertia. The authors regard the development of this simulation as a major advance in design procedure and hope that DHC will be encouraged to publish further details.

Quarter-Scale Sea Trials

'Rx' Research Craft

As part of the initial design study, DHC equipped DREA's 'Rx' craft with a $\frac{1}{4}$-scale hydrofoil system (Fig. 5). As can be seen in Fig. 21, this model differs in some respects from the full-scale ship, but the important features of weight, L.C.G. position and foil-base length are correctly represented. Bow foil modelling always kept pace with full-scale design changes but the main foil did not. For example 'Rx' has no stability augmentation system; the tips of the anhedral foils are fixed.

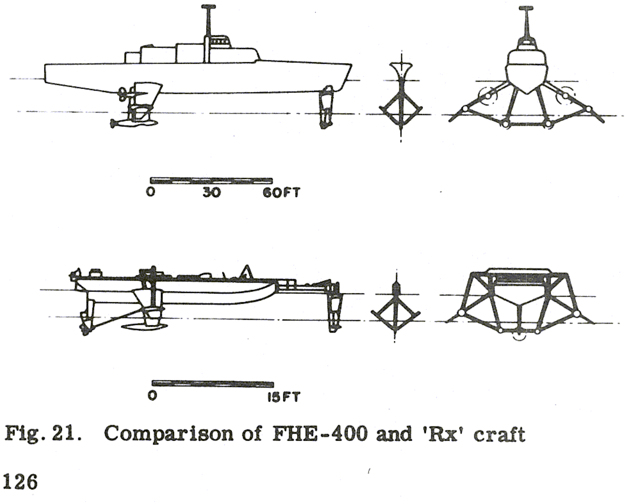


Fig. 21. Comparison of FHE-400 and 'Rx' craft

The particular advantages of the 'Rx' were that she operates in the natural environment with six degrees of freedom, the scale is large enough for ventilation effects to be apparent and the crew of two were able to experience most of the effects of the full-scale ride. Operated at dynamically (Froude) scaled speeds in linearly scaled seas, the full-scale accelerations are experienced, albeit at twice the frequency. The craft could thus be used to determine rough water loading and steering characteristics and to check the validity of the advanced analytical techniques used by DHC to predict foilborne characteristics in a seaway.(12)

It was primarily for the latter purpose that the 'Rx' program was set up, but foil design problems became apparent during preliminary tests and the craft performed an even more useful function as a practical development tool.(13) In particular, the ability of 'Rx' to demonstrate cumulative and interdependent effects provided a vital link between tank tests under rigidly controlled conditions and full-scale operation at sea.

The incidence of debris is high in harbour waters where most 'Rx' tests were conducted and this gave unlooked-for but valuable experience in impacting and impaling wood and other objects. Such encounters caused surprisingly little damage or interference, particularly considering that the debris was not quarter-scale.

Bow Foil Development

The characteristics of the novel, superventilated bow foil unit were of special interest because no practical operating information was available. These hydrofoils generate sharp lift increases if the air path is interrupted and, although this is an inherently safe situation, good foilborne seakeeping depends on smooth bow foil characteristics, free from flow reattachment effects, over the widest possible ranges of angle-of-attack, immersion and speed.

It became apparent very early in bow foil tests that the anhedral/dihedral intersections suppressed ventilation on the dihedral foils whenever they became immersed and this effect was severe enough to cause cyclic pitching over wide speed ranges in calm water. The problem was overcome by redesigning the anhedral foil sections locally at the intersections to provide a freer air path.

However in rough water, even at high speeds with the intersections clear of the water, the large changes in angle-of-attack and immersion encountered by the dihedral foils led to flow reattachment, and craft motions were augmented rather than suppressed. Fig. 22 shows a typical 'Rx' bow foil section which was developed to obtain adequate tolerance to angle-of-attack. The spoilers encourage early flow separation and do not seriously affect drag since they are within the cavity at high speeds.

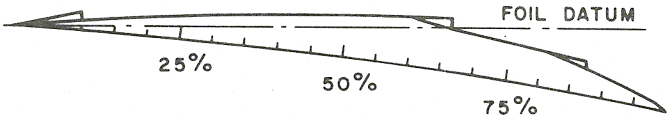


Fig. 22. Superventilating 'Rx' bow-foil section

Rough Water Behaviour

Trials experience with 'Rx' in rough water was most valuable. The results cannot be directly converted to the expected performance of BRAS D'OR because of the differences apparent in Fig. 21. Some of these favour the 'Rx' craft, such as a lower V.C.G. and the presence of a stern strut; others favour BRAS D'OR such as larger hull-clearance and the stability augmentation system. Nevertheless, 'Rx' behaviour provides a first assessment of the sea-keeping potential of the DREA surface-piercing hydrofoil concept, and as such is significant in its own right.

The 50 knot sea state 5 design condition for BRAS D'OR corresponds to waves of 2·5 ft. significant height for 'Rx' and this proved to be the most exacting condition for head sea runs. Vertical acceleration values of 0·25 g (rms) were measured at the C.G. In following seas vertical accelerations are much reduced but there is a decrease in roll stiffness and more helm is required to maintain heading.

Bow foil steering control is surprisingly good, considering that the bow foil is often completely clear of the water. Turn rates of 10°/sec. at 25 knots and 15°/sec. at 20 knots were recorded in this $^1/_4$-scale state 5 sea.

The highest sea state encountered during 'Rx' trials would correspond to full-scale waves of 28 ft. significant height, with occasional 48 ft. swells. The craft was able to take-off and maintain her design rough water speed at all directions to these 7-12 ft. waves. Head sea vertical accelerations were less than 0·2 g (rms) at the C.G., confirming that wave height is not a valid criterion. The critical point of operation was with the bow foil in the back slope of a following wave where it is subject to adverse orbital velocities for an appreciable duration. Under these extreme conditions increased bow foil rake angle was necessary to prevent negative lift, and more generally, the ability to adjust bow foil rake to optimise response in different sea conditions and directions was found to be a valuable design feature.

It is interesting to examine 'Rx' seakeeping on the basis proposed last year by Silverleaf and Cook(14). They use a wave height parameter defined by $h/W^{1/3}$, where h is the significant wave height in feet and W is the all-up weight in tons, and compare the speed loss of a variety of high speed marine craft. The 'Rx' rough water design condition corresponds to an $h/W^{1/3}$ of 1·7 at a speed 83% of maximum calm water speed. This places the craft close to the line drawn for fully-controlled hydrofoil ships in the paper and shows that the marked loss of speed attributed to surface-piercing systems at $h/W^{1/3}$ greater than 1 need not occur. Indeed, 'Rx' has maintained her rough water design speed up to an $h/W^{1/3}$ value of 4·75, although this parameter becomes invalid as a criterion at such high values.

Initial Full-Scale Trials

Trials Plans

Three areas of interest are identified in the program currently authorised. 'Scientific' trials are aimed at evaluating ship performance in relation to design predictions, with particular regard to the feasibility of the concept for sustained open-ocean operations and its application to future ship design. 'Technical' trials are aimed at evaluating the machinery, systems installations and components. 'Operational' trials are aimed at evaluating seamanship, handling and habitability characteristics of the ship.

The ship is manned and operated by Canadian Forces but the prime contractor remains responsible for the ship until completion of the pre-acceptance trials. These are primarily calm water trials intended to prove the ship ready for the open sea. All trials to date have been of this nature and under the direct control and supervision of DHC. Following acceptance, trials will be planned and conducted by a joint Canadian Forces-DHC-DREA team, with DREA responsible primarily for scientific trials.

The main objective of trials to date has been to make a quick assessment of the calm water characteristics of the ship over the whole speed range. Trials have not been made in a rigorous way and measured data are preliminary in nature. The intention was to restrict these initial operations to very calm conditions but the trials were actually run in waves varying up to about 6 ft. in height.

Hullborne Trials

Attention has been concentrated on foilborne running and few hullborne data have yet been obtained. A total of 69 hullborne hours has been accumulated, mainly on leaving and entering harbour, but enough to demonstrate satisfactory performance, control and manoeuvring characteristics. Fig. 23 shows the ship during hullborne trials.

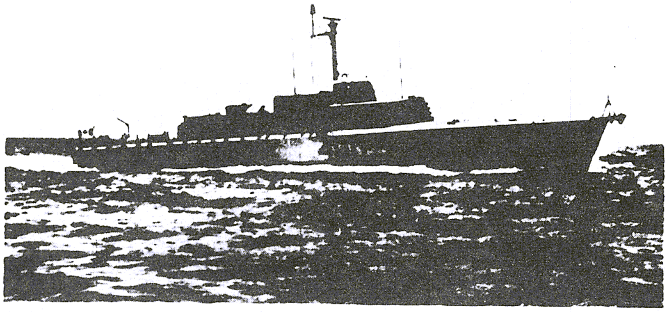


Fig. 23. BRAS D'OR on hullborne trials

A maximum speed over 13 knots was obtained on diesel power alone and bow foil steering proved effective at speeds down to 3-4 knots. Although they provide massive roll damping, the fixed main foils also lower the centre of lateral resistance and outboard heel angles up to 10° were experienced during higher speed hullborne turns. With the variable incidence tips in operation, roll angles did not exceed 4° in turns made with a wind speed of 40 knots and waves of 5 ft.

Using a combination of differential thrust and bow foil steering, low speed handling characteristics are excellent, and the ship can be turned in its own length. Berthing is also facilitated by the high lateral resistance of the foils which minimises crosswind drift.

Foilborne Trials

A total of 18·5 foilborne hours has been accumulated. Four runs were made at speeds in excess of 60 knots, with durations varying from 6 to 11 minutes and a maximum speed of 63 knots was obtained over one run in 3-4 ft. waves. Speed measurements are based on Decca fixes because the systematic measured mile runs needed for calibration of the ship's pitot-static log have not yet been made.

Because of faults in the thrust measuring system, only a tentative indication of drag has yet been obtained. A mean of all data taken in seas up to about 6 ft. yields overall lift/drag ratios of 6·5 at 60 knots, 7·5 at 50 knots, 9 at 40 knots and 11 at 30 knots, but these results cannot be relied upon.

Measured values for rise and trim are compared with values predicted by a DREA digital computer study in Fig. 24 and Fig. 25. These show a small trend towards lower rise and higher trim which could be due to ventilation at the main foil.

The ship takes off very smoothly and the pitch change accompanying the bow foil's transition to fully-ventilated flow is well damped. Flow has remained strongly ventilated over the full speed range at the design setting, except for a few instances in waves at the lowest foilborne speeds, when a small increase in rake has been required.

The only significant hydrodynamic problem so far encountered is a small 'flick' roll at speeds between 45 and 55 knots.

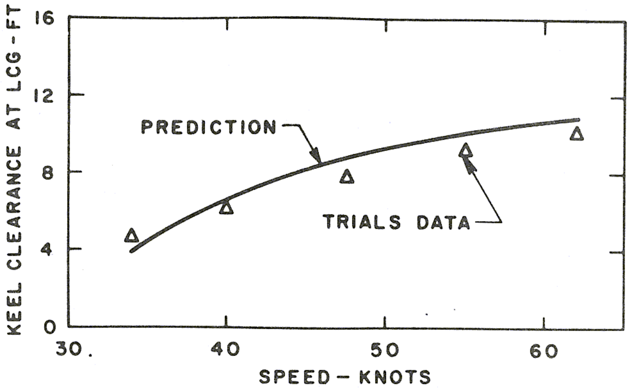


Fig. 24. Foilborne trials—Rise curve

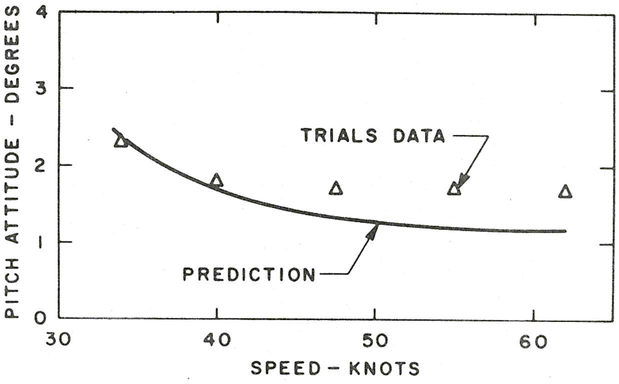


Fig. 25. Foilborne trials—Trim curve

Between these speeds the outboard-intersection pods pass through the water surface and the dihedral foils and anhedral tips are thought to be ventilating intermittently down to the first fences. Although the roll amplitude is only about 1°, the resulting motion is uncomfortable at the upper deck and wheelhouse levels, where high-frequency lateral accelerations of 0·15 g have been recorded. Extra anti-ventilation fences will be fitted and are expected to reduce these motions considerably.

Current Status

It is believed that enough sea time has been accumulated for most of the technical problem areas to be identified. The worst transmission problem has been excessive torsional oscillation which occured when high engine power was applied for take-off at maximum acceleration. This is thought to be due to the super-cavitating propellers reacting with the long, flexible drive-shafts at low advance ratios, where the propeller torque is decreasing as rpm increases. The problem can be readily avoided by decreasing the take-off rate but detailed analysis, perhaps with additional propeller model tests, will be required to confirm the basic cause and suggest the best solution.

Undoubtedly the most serious problem has been cracks which have developed in the horizontal centre main foil. At the time of writing an investigation is still under way, but it appears that a leak developed in the foil some time ago, allowing stagnant seawater to attack unprotected metal from the inside, and resulting in extensive stress corrosion cracking in and near welds. A replacement foil is planned and, in the meantime, hullborne trials will continue with a temporary simple foil made of mild steel.

There have been other technical problems, ranging from overheated downshaft bearings to false fire alarms due to sunlight reflections in the stack, and frustrating delays while these have been overcome. This is expected in a project of this nature. There is every indication from initial trials that both the concept and the design are fundamentally sound and that the program objectives will be met.

5. FUTURE PROSPECTS

Although the evaluation of HMCS BRAS D'OR remains in its infancy, a sufficient body of design and $1/4$-scale sea experience has been accumulated to warrant a tentative look at future prospects, both for the surface-piercing hydrofoil concept in general, and for the Canadian program in particular. Any such discussion inevitably invites a comparison with hovercraft, but this is taken up only to explain the authors' conviction that these vehicle types are complementary rather than competitive.

Hydrofoils and Hovercraft

Studies have been made to compare the potential merits of hovercraft and hydrofoils in various roles within the 'small and many' context, considering craft in the 100-500 ton range. These suggest that the most significant factors are:-

(a) The proportion of time the craft is required to operate at high and low speeds

(b) The relative importance of speed and seakeeping ability.

In a hovercraft, the basic hull shape is dictated by the concept to a greater extent than in the hydrofoil. As discussed, a properly designed hydrofoil system can enhance the slow speed seakeeping behaviour of a conventional displacement hull, to an extent not possible with hovercraft, even of sidewall type.

Apart from its obvious and unique capability for amphibious roles, the major advantage of the hovercraft lies in the absence of the 60 knot 'barrier' imposed on the hydrofoil by cavitation. However, the same criteria of human response apply and to exploit their higher speed potential, hovercraft will have to platform. Feasible clearances deny such operation under all-weather open-ocean conditions to craft of the envisaged size.

At the present stage of the development of both hovercraft and hydrofoils it is dangerous to press these comparisons too far. The important point to emerge from these studies is that, if the roles are properly selected to exploit their capabilities, then these two types of craft are complementary, not competitive. Development should concentrate on the most appropriate roles, and some examples worthy of study are listed in Table V. It is strongly felt that the role of HMCS BRAS D'OR is in keeping with this principle.

Surface-Piercing and Fully Submerged Hydrofoils

The simplicity of fixed surface-piercing foils makes them an attractive alternative to more sophisticated fully-submerged systems for some applications. Experience with models and an open-water test craft has demonstrated considerable promise of reliable rough water operation, and suggests that the major shortcomings of earlier surface-piercing systems have been overcome. In particular, the seakeeping potential appears much higher than previously thought and surface-piercing systems could have important applications, not only in military roles, but in any situation where a high degree of contouring is demanded, and particularly in the smaller sizes of seagoing craft where an automatic control system may represent a significant fraction of the total cost.

It is interesting to relate the potential to the comparisons of seakeeping presented by Silverleaf and Cook(14). Hydrofoil craft can be designed for a hull clearance of about $1{\cdot}5\ W^{1/3}$, where W is the displacement in tons. This means that the range of non-dimensional sea heights considered by Silverleaf

TABLE V Some Appropriate Applications

HYDROFOILS	HOVERCRAFT
To exploit:	To exploit:
1. Seakeeping ability c.w. size	1. Extreme calm water speed
2. Enhanced slow speed behaviour	2. Amphibious potential
Military	*Military*
Open ocean ASW escort	Assault Amphibians
Coastal ASW and COIN Boat	River Warfare Boat
Fast Patrol Boat	Arctic Patrol Craft
Search & Rescue Boat (Open Water)	Search & Rescue Boat (Shoal Water)
Commercial	*Commercial*
Coastguard Cutter	River Ferries
Oil-Rig Work Boat	Shoal Water Ferries
Open Water Ferries	Sheltered Water Ferries
Pleasure Cruisers	Sports Craft

and Cook (their Fig. 3 and Fig. 4), extends only slightly beyond the feasible extent of the platforming regime. Within this range, both fully-submerged and surface-piercing hydrofoil craft can be designed satisfactorily, although the fully-submerged foil system will provide a much more comfortable ride.

An increasing degree of contouring is involved beyond this range and wave steepness becomes the controlling parameter rather than wave height. No system can be truly comfortable in a contouring situation and the fully-submerged foil begins to lose its advantage. The surface-piercing system is expected to have a higher potential ability; the unresolved question is whether the crew will be able to exploit this potential. Best evidence from $\frac{1}{4}$-scale manned model trials is that they will, but the true limits can only be established from full-scale experience.

These remarks apply to craft designed for the delayed-cavitation range of speeds. At higher speeds it is unlikely that any significant degree of contouring will prove tolerable by the crew. Current thinking is that 50-60 knots is the upper limit of all-weather open-ocean speeds for all types of hydrofoils (and hovercraft) in the 100-500 ton class. Indeed a major jump in size may be required to exploit higher speeds, because the occasional higher wave will impose a serious threat once the design philosophy is restricted to pure platforming.

The reverse is also probably true. Unless smaller pay-load ratios are acceptable for some specific purpose, any major increase in size will require the design speed to rise, and hence demand a jump into the supercavitation regime. This will introduce structural and hydroelastic problems of a new order, and developments in materials are likely to govern the timing of this major step.

From the Canadian point of view, the value of such developments is unresolved. Certainly it would seem that all-weather craft in the supercavitation regime will not fall within the context of the 'small and many' concept, and no requirement for large hydrofoil ships or hovercraft has been clearly established at this time.

The Canadian Program

Assuming that the evaluation of HMCS BRAS D'OR proves the concept of the hydrofoil as an ocean-going all-weather vehicle, authority will be sought to install the fighting equipment and her evaluation as an ASW system will commence. This will take the form of technical trials to determine the performance of the fighting equipment, extended cruises to confirm long-term habitability and associated factors and, finally, operational exercises with the fleet.

A major objective of this phase of the program will be to establish firm operational requirements based on realistic tactics. Obviously the best tactics for hydrofoil ships will differ from those developed for more conventional vehicles, but only operational experience can show exactly how. When the concept was originated, assumptions had to be made regarding probable tactics to define the required hullborne and foilborne speeds, endurances, manoeuvrability and other characteristics of the ship and its fighting equipment. Undoubtedly these requirements will undergo some revision in the light of operational experience.

Although there are no formal plans for follow-on construction, the possibilities are obviously being borne in mind in evaluating BRAS D'OR. In addition to design modifications to meet revised operational requirements, improvements can already be forseen in some technical areas. They centre around a single aim of simplification.

In developing so radical a concept it is inevitable that the prototype emerges considerably more complicated than originally envisaged. There is no single major component likely to prove dispensable, except possibly the stability augmentation system, and even this may be justified by the added manoeuvrability it confers. Rather there is a need to review the entire content of the ship, particularly in the areas of machinery and fluid systems, for possible simplification.

Moreover, it may prove operationally feasible to reduce the maximum speed. Within the delayed-cavitation regime the top few knots are very expensive in terms of structural design. Hull-clearance is another very expensive parameter, and one which may prove to have been cautiously over-proportioned. Recent developments in sonar towing will also ease certain requirements.

A fundamental point is that all the changes foreseen between BRAS D'OR and her possible successor involve walking back towards simpler and more conservative design practice. Data obtained from BRAS D'OR trials, properly interpreted, should suffice and no extrapolation will be involved. This means that it should be possible to proceed directly to a 'first-of-class' design intended for quantity production.

6. CONCLUDING REMARKS

The aim of the Canadian Forces hydrofoil program is to develop the smallest, simplest and least costly vehicle which can operate with reliability and habitability at hullborne and foilborne speeds in the open ocean, having a high degree of effectiveness in all phases of ASW.

The program has not reached a state at which firm conclusions can be drawn, but completion of HMCS BRAS D'OR is a major milestone and results of preliminary trials are promising. In relatively calm water (0-6 ft. seas) the ship has exceeded her design speed of 60 knots and has demonstrated good stability and control at all speeds.

No trials have yet been run in rougher water, but a manned quarter-scale test craft has provided good evidence of all-weather capability, and has shown that the seakeeping limitations of earlier surface-piercing hydrofoil systems have been overcome in the DREA-DHC concept.

Contrary to popular belief regarding the relative merits of fully-submerged and surface-piercing foils, neither system is universally superior. Each has its advantages for particular roles and the comparison will vary with size and speed. Hybrid systems can also be developed for specific application, combining certain merits of both approaches. In the present state of the art the important task is to gain a thorough understanding and ocean-going experience of both systems, so that the future designer will have a full repertoire of choices available to him.

In general, hydrofoil development has reached a stage where the simplest types of subcavitating craft are both feasible and economical. Several hundred hydrofoil ferries are now in successful commercial operation throughout the world, ranging from 15 to 150 tons and with top speed of 30 to 40 knots. Sizes from 200 to 500 tons and speeds of 40 to 60 knots are technically feasible but their use is currently limited to military applications where the cost of additional performance is justified by tactical necessity. The supercavitation regime remains speculative and full of challenge.

Students of aeronautical history will note the similarity of the pattern, and it is not surprising. The practical engineering of hydrofoil craft is governed by the same basic restraints of available power plants and structural materials. Predicting the long-term prospects for hydrofoil craft is as difficult today as it was for the committee of experts less than sixty years ago, who proclaimed that 'due to restrictions in size and weatherliness, there is no place in modern warfare for the aeroplane.'

ACKNOWLEDGMENTS

Much of the descriptive material in this paper has been taken from unpublished reports of the DeHavilland Aircraft of Canada Ltd. and to this company goes the credit for an outstanding engineering achievement. The authors would like to thank Capt. T. S. Allan, Canadian Forces Hydrofoil Program Manager, Cdr. C. Cotaras, Commanding Officer, HMCS BRAS D'OR, Cdr. J. H. W. Knox, Project Systems Engineer (FHE-400), Mr. R. W. Becker, DeHavilland Hydrofoil Program Manager, Mr. B. V. Davis, DeHavilland Chief Hydrodynamicist, for their personal assistance, and their teams for a major contribution to naval science. They would also like to thank their many colleagues at DREA who have contributed to the program, and hence to this paper.

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DISCUSSION

Mr. P. R. Crewe, M. A. (Associate-Member): Perhaps the best reason for me to open the discussion is that my paper before the Institution on hydrofoil boats, in 1958, is the first reference in the present paper. I should begin by congratulating the authors on a paper which I found exceptionally good in that it told me nearly everything I wanted to know, not only the successes of the programme so far, but also the problems met. It gives a very fair picture of where this type of hydrofoil boat has reached at the present stage. Since the days when I was associated with an earlier Canadian hydrofoil boat, also named BRAS D'OR, my own concern has been mainly with hovercraft. It is very interesting to find that much of the discussion on basic stability, and the design features of importance with regard to this, reads across to the hovercraft situation.

Referring to the section on stability, Fig. 7 lists three different types of motion, platforming, contouring, and intermediate response. It is the last type, in very large waves, that the BRAS D'OR is particularly designed to meet. The same is true of large hovercraft. They are not designed to platform or to contour, but instead to have this intermediate type of response. When claiming advantages for the hydrofoil it should be borne in mind that the power to weight ratio of HMCS BRAS D'OR is over

150, which is 60% more than that of the SR.N4 hovercraft of comparable size. If the latter had 60% more power, the options available to the Hovercraft designer would be greatly increased; and in particular much more lift power could be employed to provide an intermediate response type of heave motion much closer to that of BRAS D'OR. Another interesting figure here is the 34% structure weight, compared with order 34/37% for hovercraft. In that respect, it is interesting that BRAS D'OR is a very high density craft and would therefore be expected to have fairly low structure weight. Thus the structure weight penalty of foils tends to offset that of skirts in a hovercraft.

I would like to ask one or two questions, even though security considerations may prevent their being answered. First, propeller wear. Is it possible to say what the propeller life is, at this stage? With regard to problems—that of foil material was mentioned—and I wonder whether leak detectors have been built into the system so that much more rapid action can be taken in future if leaks occur.

The authors have stressed that many complications were built into this original craft, that can probably be eliminated in production craft. I only wish we had been able to do the same thing in hovercraft, as such a practice may have a great deal to do with the rapid success of a project.

It seems to me that in the present state of the art, big hovercraft and the BRAS D'OR type of hydrofoil boat have reached comparable stages of development. Neither of them is perfect, but both are promising. I hope for a continued amicable competition between the two types. Would the authors agree?

Mr. A. J. Vosper, R.C.N.C. (Member of Council): In the Introduction to the published version of this most interesting paper, the authors make the point that the advent of nuclear power has had a significant effect on the high speed potential of the submarine, in that the designers can now design without too much regard to surface performance. In the same way, the satisfactory foil system which the authors describe allows the hydrofoil craft designer to exploit its high speed potential above the water surface. However, I think it is most important in this context to bear in mind that the ability to get away from the surface, in either direction, up or down, is not achieved without paying a price in terms of weight and space limitations available for weapon systems, machinery and so on. It will be obvious that below the surface, problems such as pressure hull design have to be faced and heavy weight of structure limits submarine performance. Above the surface, in the same way, the hydrofoil craft is carrying quite a heavy foil system—18·6% of all-up weight is quoted in the paper, greater than the total hull weight, in order to achieve its high speed, rough water capability in the foil-borne condition. This must similarly impose severe limitations on the craft's military payload. Does therefore the 'small and many' concept for ASW hydrofoil craft show up favourably, on a basis of cost effectiveness, in comparison with, say, a conventional helicopter destroyer? This is an aspect of military hydrofoil craft design which prospective customers must look at very carefully.

My second point concerns the authors' interesting comments about favourable performance of the BRAS D'OR in its hull-borne mode. The claim is made that the predicted motions from model tests and from measurements in the research craft are comparable with those of a conventional warship of at least 3,000 tons. Whilst it seems reasonable to expect that the large damping provided by the fixed foils will have a beneficial effect on rolling motion, and will affect pitching to some extent, I find it difficult to believe that their effect on pitching can be so marked as the claim suggests, particularly as we are comparing ships of lengths of about 150 ft. and over 300 ft. respectively. Some actual figures for motion in the hull-borne state would be very much appreciated.

Finally, it must be a great disappointment to Mr. Eames not to have been able to give a more comprehensive report on the evaluation trials because of the unfortunate delay in evaluating the foil-borne condition due to cracking problems in the main foil. When these have been overcome, I very much hope that we can look forward to some further publication of the BRAS D'OR's performance.

Mr. C. Hook: It was very exciting to see the beautiful pictures and films used during the introduction of the paper, which were superb. Mr. Eames said that the choice was made on the basis of avoiding moving parts. Back in 1946, when I started in England, this was the first reply I got from the National Physical Laboratory, and hydrofoils were not looked at with favour because of this. One has to weigh up the relative advantages and disadvantages in various fields, and you are sacrificing so much, e.g. the ability to retract, as the foil system is completely rigid, and the draught of the boat is very great. I understand that the Canadian Navy does not suffer from this, because there is a deep sea port at Halifax, but this must be a great disadvantage for most navies, and for police boats, etc.

With reference to moving parts, the Americans specialise in the incidence control craft, and have brought out boats too expensive to buy and maintain. The Canadians have specialised in step ladder foils and are faithful to the Bell family tradition in producing this type of craft. But in a seaway, this fixed incidence craft, in order to deal with this intermediate type between platforming and contouring, has to pitch the whole boat, whereas if you have incidence control via mechanisms, you only move your mechanisms, and not the boat.

Mr. A. Silverleaf, B.Sc. (Member of Council): This paper is a splendid addition to the literature in our Transactions relating to high speed marine craft. Its description of an exciting and major project was enhanced by the films we have just seen and, although this form of presentation is not quite so unusual as Mr. Eames seemed to suggest, it did bring out many of the major problems involved in a project of this kind, though neither the films nor the paper itself show just how difficult it was to overcome many of them. Nor, naturally enough, does the paper give the authors and their colleagues sufficient credit for some of the intuitive as well as analytical approaches which they developed to overcome difficulties which often seemed to be insuperable.

I have been concerned with the design and evaluation of foilcraft for almost 30 years and the ten-year period during which we at NPL have worked with Mr. Eames and his team is one of the most satisfying episodes in this long association. The message we received at NPL just over a year ago from the BRAS D'OR team, telling us that within the past 24 hours the craft had reached a speed of over 60 knots, was a memorable highlight, and it is most encouraging to hear that further trials are showing such good performance characteristics.

The paper has an excellent balance between operational and design features and this is particularly valuable in the context of the growing literature on foilcraft. In particular, the authors are frank in their important admission that at first the DREA went astray in following too closely the Bell-Baldwin practice, and their discussion of the principles of foil systems demonstrates the advances made during the past decade or so. I should like now to comment on one or two particular points which relate closely to views on high speed marine craft I have presented to this and other Institutions during the past year. First, the payload ratio of 37% for BRAS D'OR is as good as has been achieved for any high speed marine craft of reasonable size. Did the authors consider that the cost of achieving this extremely high payload ratio has been particularly great, both absolutely and in terms of cost-effectiveness? Next, the discussion of motion control systems deals in a fairly conventional way with surface-piercing and fully-submerged types of foil. However, I think it more useful to talk in terms of surface sensing or motion sensing systems since this distinction leads to a better understanding of what can and should be done in particular situations. Incidentally,

disposal load

I do not find reference in the paper to any motion controlled device fitted to BRAS D'OR; are there not movable control surfaces at the tips of the main foil aft? In presenting the paper Mr. Eames stated that the cost of an automatic control system would be significant. All the information I have is that this is not so, and that automatic control systems add very little to the total cost of craft of reasonable size.

The final section of the paper discusses future prospects for foilcraft and hovercraft. It is natural that this discussion is slanted towards naval roles but perhaps this gives a slightly false impression of the broader issues. Many of the arguments so succinctly summarised about the particular features of naval requirements do not apply with the same force—and sometimes not at all—to civilian commercial tasks. There is no reference to economics, which dominates commercial exploitation, although the important conclusions in the paper about the size and speed of future foilcraft and hovercraft may well be as valid for commercial as for naval craft. One of the films we saw mentioned that in 1919 the early HD4 did not catch on because there was no tactical demand for a craft of that kind. That phrase has a very familiar sound to it, particularly if it is translated into the context of commercial operation. Twelve years ago, in discussing Mr. Crewe's paper to this Institution(1), I asked, 'Is the air-water interface the best place for really high speeds?' Regretfully, more and more I feel that the answer may be 'No'. However, even if enthusiasm for high speed marine craft has to be tempered by practical realities, this does not detract from the virtues of this admirable paper.

Professor G. Aertssen, (Member): It is always a problem to get small ships through the rough water of the open ocean. There was a solution with trawlers, and hydrofoil ships can get through it. Like trawlers, this 200 ton, 50 knot hydrofoil will not be so much concerned with the components in the wave spectrum at high and low frequency. She is platforming on the high frequency components and contouring on the low frequency components, but the difficulties arise in the intermediate part of the spectrum.

Coming to the rough water behaviour, on page 127, I see that facing waves in a sea state Beaufort 5, at 50 knots, the vertical centre of gravity acceleration is 0·25 g, r.m.s., which means a maximum of 1g. Even conventional ships attain this acceleration, but at the bow. Therefore I would like to have the authors' opinion on the increase of acceleration along the ship, at the bow and at the stern. On the other hand, a significant wave height of 2·5 ft. is mentioned, for a sea state 5. Is this not too low for the open ocean? Also, what about lateral acceleration, especially in a following sea? Finally, on seakeeping qualities, has some work been carried out on these at hull-borne speeds? I share the enthusiasm of the authors.

The Chairman, Mr. R. N. Newton, R.C.N.C. (Vice-President): I recall a NATO Naval symposium in 1961, in Church House, in which Mr. Eames took part and at which the 200 ton Canadian Navy and the 300 ton U.S. Navy hydrofoil craft were first put forward as possibilities. Several representatives who attended were sceptical about these proposals. It is gratifying to those who were not so sceptical, that nine years later, we are permitted to see a film of the actual performance of the craft that Mr. Eames and his associates were planning in those days.

You will have noted that the first film faithfully followed through the actual paper and as such was very educative and very interesting. I must say that even if it was time consuming it is a very effective way of presenting a paper. On your behalf, I should like to thank the Canadian Defence Research Establishment, and the Canadian Navy, for allowing all the information to be published in the paper and Mr. Eames for presenting it so ably. I venture to suggest we may see him again in two or three years, with the full results of the rough water trials. We are very grateful to him and I ask you to show your appreciation in the usual manner.

The vote of thanks was carried with acclamation.

WRITTEN DISCUSSION

Mr. A. K. Buckle, B.Sc. (Member): In the films accompanying the presentation of the paper, reference was made to the 'take off' speed as being 20 knots in calm water, 26 knots in head seas and 28·6 knots in following seas. This variation is most surprising. Could the authors say how it comes about? Perhaps changes can be induced by suitable adjustments of the angle of attack of the bow foil and main foil extensions, and this is done as a deliberate operating technique in rough sea conditions.

Could the authors give values for measured impact loads of wave crests on the craft's hull?

In particular, can figures be quoted of variations in pressure with changes in the area of impact under consideration? Experience with commercial hydrofoils indicates that the maximum impacts over small areas, i.e., below 12 in.^{2}, can be very high. This seems to be due to the vertical motions of the waves relative to the vessel, being in practice, sufficient to double the pressure values predicted if stagnation pressure is based on the craft's forward speed alone. Are such values also found to occur on the BRAS D'OR? From the data on scantlings so far published, it would seem that they are.

On page 116 of the paper the authors refer to fencing and say it is a process of trial and error. Could they please expand this with particular reference to the errors—especially as it is noted that the shape of some of the fences, as finally fitted, have a rather unusual outline.

Commander Peter Du Cane, C.B.E. (Member): This is an interesting paper and certainly makes a case for the surface piercing hydrofoil.

What, of course, is of paramount importance in forming a judgement on the merits of this system is to know how it compares with the fully submerged controlled foil system used mostly in the U.S. naval craft of this type as also with hovercraft, and indeed semi-displacement craft possessing similar characteristics so far as useful load, power required and cost are concerned. Also, and by no means least, how do the realistic seakeeping properties of these types compare.

The place where this craft lies on the various comparative performance curves in Ref. 14 will be of interest, though being a prototype the figure for the criterion of cost per ton knot will be unrealistic, but very important for the long term in the form £ Sterling per useful ton knot. As a matter of, perhaps, some interest my firm designed to meet this Canadian enquiry a seagoing semi-displacement craft on the basis of a hull form which had performed very well in seagoing fast patrol craft. The length of this craft was 174 ft. driven by two Olympus marine gas turbines for high speed of 50 knots in Sea State 5 and two Deltic high speed diesels at cruising speed of 18 knots. The useful load was 60 tons, considerably more than suggested for BRAS D'OR.

In 1962 model tests on this hull form carried out by the Netherlands Ship Model Basin in irregular head sea corresponding to significant wave heights of 3·1 m (Sea State 5) indicated that acceleration at midships would be about 0·55g in r.m.s. terms (N.S.M.B. Report No. 99, Oct., 1962). At that time this compared with a value of 0·37g for the BRAS D'OR in the same sea state according to some records I was shown. If this is substantially different from actualities, I can only apologise but the relative figures seem to make reasonable sense.

The price so far as we could make comparisons at that time was much less than the hydrofoil concept. The craft in question is shown in Fig. 26 and the various points on curves ex Ref. 14 and also shown in Figs. 27-30. The interesting point to note is that the appropriate point on the curve in Fig. 30 is very much below that shown by the authors of Ref. 14 for semi-displacement or planing craft. The reason for this is due to

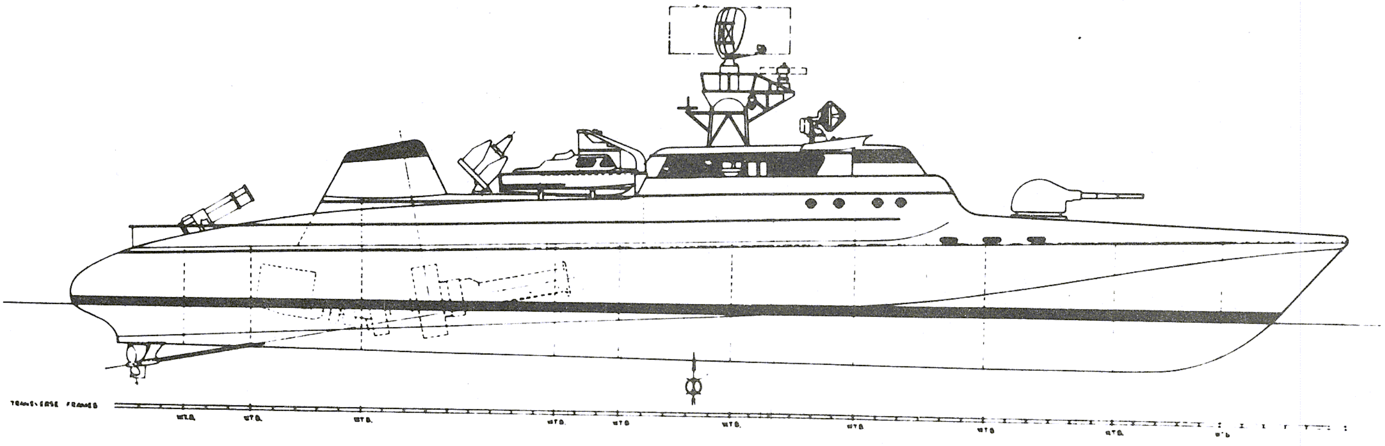


Fig. 26

the length of this craft and the relatively low $V/\sqrt{L}$ or $V/\Delta^{1/6}$ at which it is running at 50 knots.

Finally, in considering this very interesting paper, I should like to ask the authors to explain their Fig. 19 where the drive to the super cavitating propeller appears to run both forward and aft from the vertical shafting, whereas there appears to be only one propeller at aft end of each pod. Again I feel the designers and constructors of this interesting ship are to be congratulated on this, the first warship to exceed 60 knots—presumably at light load.

Mr. B. Long, B.Sc. (Member): In the spring of 1969 I was able to spend a few hours aboard HMCS BRAS D'OR (I believe it was the day she made her first foilborne turn) and can vouch for the almost unbelievably high standard of design and manufacturing expertise which went into this remarkable ship. I only regret the implications of the fact that it was found necessary to employ an aircraft firm as prime contractor.

I found the paper itself of great interest, but feel that its value would have been greatly enhanced if we knew just when it had been written. For example, how many months of trials were necessary to log the first 18·5 foilborne hours?

While the authors acknowledge the advantage of retractable foils for operation in harbours they also state that berthing HMCS BRAS D'OR is not a problem in the envisaged role. I would have thought that berthing would be a recurrent problem for a small warship having a draft of 23 ft. 6 in. and maximum submerged beam extending 22 ft. beyond the side-shell. At present this vessel can only berth alongside a specially designed pontoon, and Halifax N.S. contains the only such pontoon. The requirement for such a special facility would seem to place severe operational limitations on similar hydrofoils in the 'small and many' ASW concept.

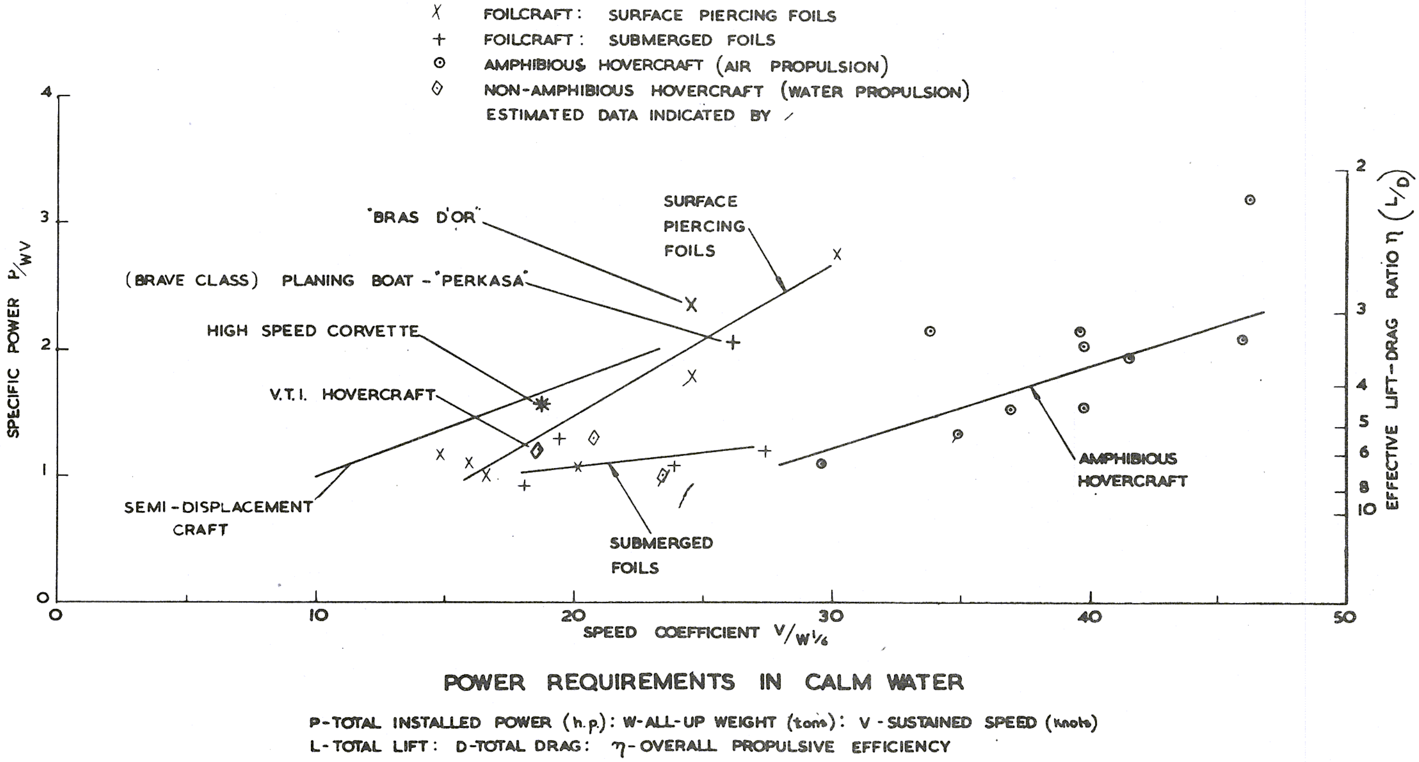
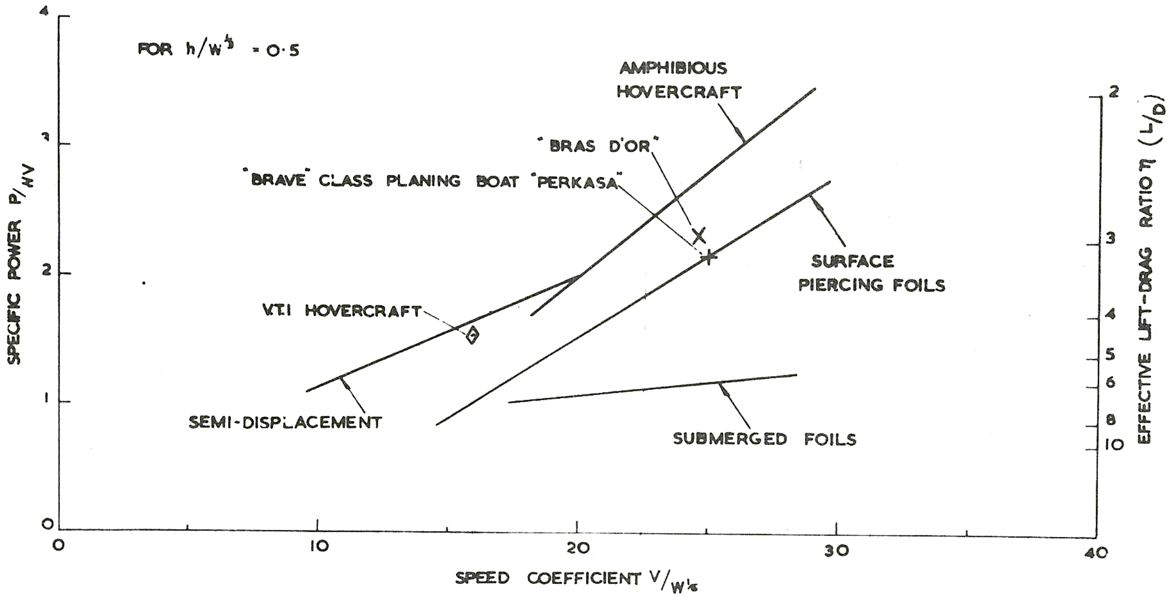


Fig. 27



POWER REQUIREMENTS IN MODERATE SEA CONDITIONS

P-TOTAL INSTALLED POWER (h.p.): W-ALL-UP WEIGHT (tons): V - SUSTAINED SPEED (knots)
L-TOTAL LIFT: D - TOTAL DRAG: η - OVERALL PROPULSIVE EFFICIENCY
h - SIGNIFICANT WAVE HEIGHT (feet)

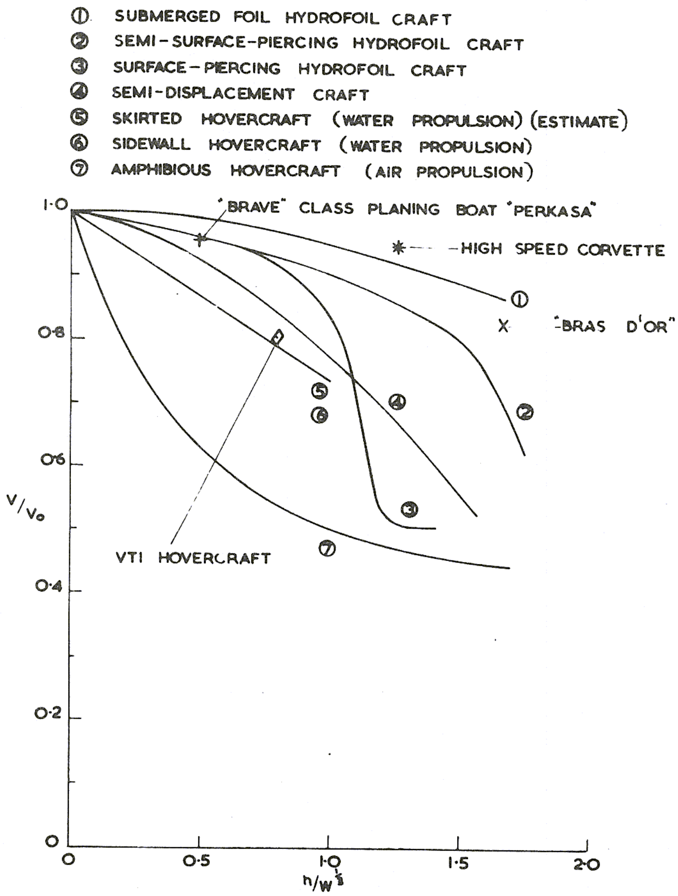
Fig. 28

We are told just enough about foilborne motion to be tantalising. The occupants of the wheelhouse, for example are strapped into aircraft-type seats, yet even they find a high frequency lateral acceleration of 0·15 g to be 'uncomfortable'. What arrangements are made for the comfort (and safety) of other crew members under such conditions? What are the 'acceptable' vertical accelerations used in calculating the limiting operational conditions, and what is their associated frequency? How have the crew fared in rougher water trials since the paper was written?

I believe that a substantial portion of the development and production costs of HMCS BRAS D'OR lay in the use of 18% nickel maraging steel for the foil elements. It was interesting to hear that in spite of the highest standards of fabrication procedure and subsequent inspection, stress corrosion cracking did occur in a main foil member. (I wonder if the protective neoprene coating had encountered some full-scale debris?) The prospect of this happening to an ASW vessel after less than 20 hours of foilborne service is obviously disturbing. In the light of information now available, would a second similar hydrofoil use a more orthodox—and more easily fabricated—steel for the foils?

Finally, in the paragraph headed 'Laboratory Model Tests-Hullborne Behaviour' I have a feeling that the authors are talking too fast for me. While I can appreciate the 'massive damping effect' the submerged foils have on hull motions, I find it hard to believe that the vessel 'will pay little or no penalty for the fixed hydrofoils in hullborne operation'.

Mr. C. T. Ray: The BRAS D'OR paper by Mr. Eames and Mr. Jones presents an uncommonly complete and informative insight into the background, objectives and accomplishment of and prognostications for the Canadian hydrofoil programme. We cannot agree however, with those portions of the paper where comparisons are drawn between the open-sea performance of craft employing the submerged, foil concept and the predictions for BRAS D'OR with her piercing foil configuration. The authors have suggested that both types of craft can be expected to have comparable seakeeping characteristics in seas in which the wave heights significantly exceed the hull-



SPEED-WAVE HEIGHT CHARACTERISTICS

W-ALL-UP WEIGHT (tons): h - SIGNIFICANT WAVE HEIGHT (feet)
V-SUSTAINED SPEED IN WAVES OF HEIGHT h (knots)
V_0-SUSTAINED SPEED IN CALM WATER (knots)

Fig. 29

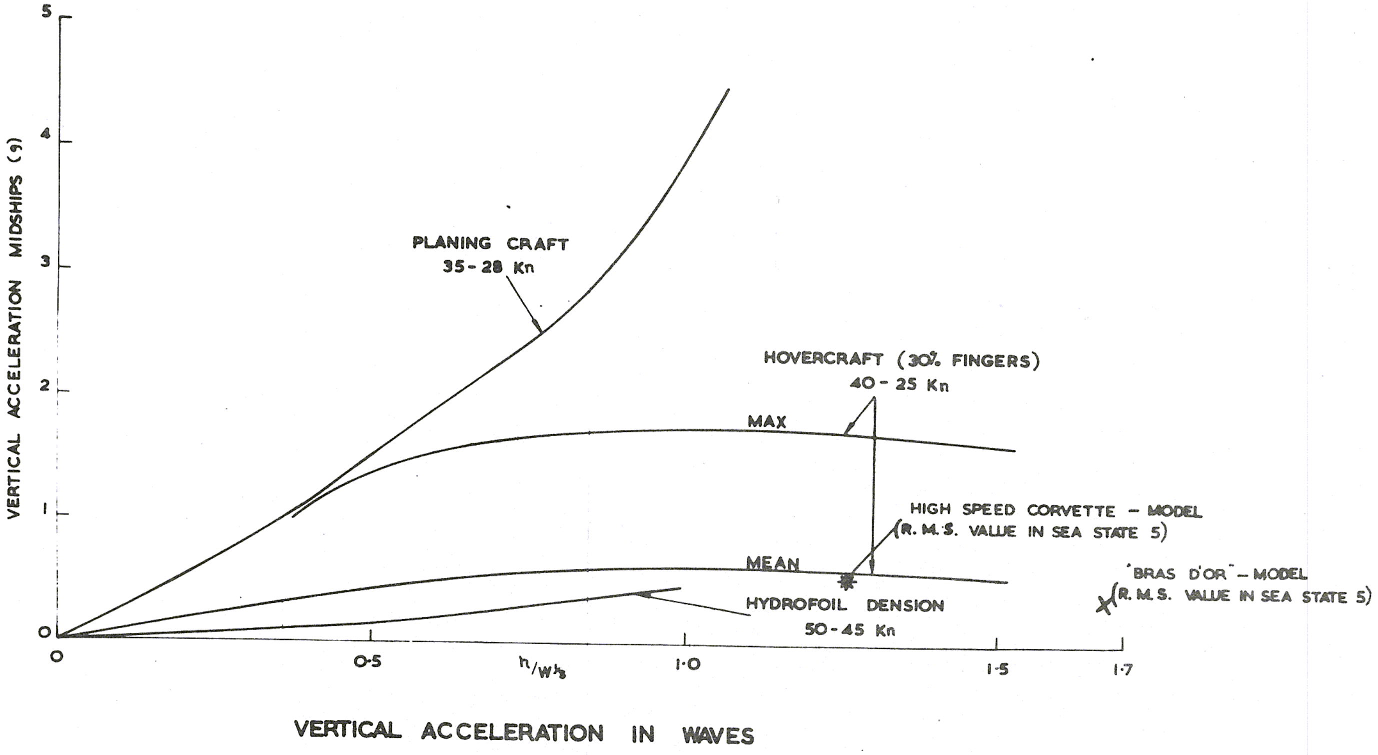


Fig. 30

clearance. This assumption must be based on the use of an analytical model that attributes common operating characteristics to both types of craft in this limiting sea condition. Hydrofoil rough water trials experience in the United States over the past few years has encompassed many hours of operation under conditions that properly can be classified as open-ocean seas and specifically under conditions of significant wave height exceedance of strut length. These trials have shown the early intuitive concepts of platforming and contouring as applied to submerged foil craft to be grossly in error.

As a result of our trials experience, it is possible to enumerate certain important and fundamental differences in the inherent behaviour characteristics of submerged foil craft as contrasted to surface piercing craft in heavy seas. The mean operating depth of the forward foil of a submerged foil craft can be selected arbitrarily and virtually independently of trim or speed. Proper use of this capability permits the foils to be operated at a mean depth that exceeds the mean keel clearance. Such operation in heavy seas grossly and advantageously violates the ideal 'intermediate response' cited by the authors in which the keel is kept dry. For example, by maintaining the forward foil well immersed at all times, it is possible to utilise the full force capability of that foil for control to achieve effective platforming operation in seas well above those for which the authors would expect contouring to be required. In such platforming operation, the action of the forward foil is to minimise the pitching and vertical accelerations associated with significant keel immersion in wave crests. Typically, the forward submerged foil will even develop negative lift in the process of minimising accelerations; in contrast to the increased lift developed by the forward surface-piercing foil in pitching the bow to 'climb over' a wave crest in a contouring mode.

The foregoing should not be construed as implying that it is impossible to achieve contouring with a submerged foil craft. On the contrary, under those sea conditions for which it would be prudent to superimpose a measure of contouring upon the previously described 'platforming' operation, the functional flexibility of automatic control permits this to be accomplished in a much more precise and effective manner than would be achievable with a surface piercing craft. The authors demonstrate awareness of this capability as evidenced by their observation that, '...the ability to adjust bow foil rake to optimise response in different sea conditions and directions was found to be a valuable design feature'. The important point to make here is that severe constraints on the efficacy of contouring are imposed by the geometry of the hull and foil system with respect to wave slope and by the accelerations associated with even an 'intermediate response' type of contouring. For the most part contouring can be characterised as a prudent mode of operation in truly heavy seas only at headings other than head and following or if sea conditions are decaying and swells prevail.

Within the constraints imposed by security regulations, we wish to correct statements regarding postulated wave height limitation for submerged foil systems. The authors have identified the condition for which the significant wave height equals $1{\cdot}5\ W^{1/3}$ as representing the feasible extent of the platforming regime. Our experience has shown that the previously described operation of a submerged foil craft can be maintained in seas for which the significant wave height is much greater than $1{\cdot}5$ times $W^{1/3}$. (Security limitations prevent the statement of the specific number). Further, such operation is characterised by no disproportionate increase in accelerations as one would expect in the transition from platforming to contouring.

The authors' comments under 'Seakeeping Ability' and 'Surface-Piercing and Fully Submerged Hydrofoils' appear to be directed toward giving the impression that submerged foil craft will exhibit a disproportionate increase in accelerations for the higher seas in which idealised platforming is impossible while the surface piercing craft will experience a decreasing trend that will lead to comparable responses in heavy seas. The foregoing discussion is addressed to the question of the purported increased accelerations of the submerged foil craft. We fear that the authors are doomed to disappointment in their expectations of reaching a point beyond which increased wave height will have no effect on accelerations in ships of the size of BRASD'OR. One can deduce that either they unduly minimised the effect of the velocity of the craft on wave encounter frequency or they have assumed that operation in heavy seas would be restricted to near beam-sea conditions where the encounter frequency is close to the fixed point wave frequency. Under the latter conditions, in waves of fixed steepness, the proportional increase in acceleration due to wave height would be exactly cancelled by the decrease of acceleration in inverse proportion to the square of wave frequency.

It should be recognised that these comments on the submerged foil craft apply to the minimal size ship (approximately 150-200 ton) in open ocean in the same sense as the authors' original premise. As the authors have noted, increasing the size of the submerged foil craft to 1, 000 tons, for example, reduces the problem of open ocean operation to the trivial (but salutary) case of near idealised platforming. Unfortunately we do not expect the surface piercing craft of 1, 000 tons to realise corresponding benefits from increased size since, regardless of hull clearance, the forward foil still must follow the surface of the disturbed sea.

AUTHORS' REPLY

We are gratified by the interest that this paper has evoked, as measured by the quality of the discussion, and we wish to thank all those who have participated and thereby enhanced the value of the paper. We were particularly pleased with Mr. Silverleaf's reference to the satisfying association built up between NPL, DREA and DHC personnel during the development of HMCS BRAS D'OR. One of the most rewarding aspects of a challenging project such as this is the opportunity it affords for working closely with so many people who are in the forefront of their professional specialty, and it is good to learn that some of these benefits are felt to be mutual.

Understandably, the most popular topic of discussion has proved to be the seakeeping ability of the ship. Comments vary from simple requests for information to polite but forceful expressions of disbelief in our predictions. We feel that the only satisfactory method of response is to take up the kind invitation of the Chairman, Mr. Newton, to return with a second paper as soon as rough water trials have been completed. To reiterate our predictions in more detail seems fruitless at this stage. Suffice it to say that the agreement between predictions from quarter-scale trials and the results of full-scale trials in sea heights up to 6 ft. gives us good confidence that these predictions will remain valid in higher seas. While acknowledging the importance of their questions, therefore, we will ask Messrs. Vosper, Aertssen, Buckle and Long to await replies based on factual information from full-scale trials.

In the meantime, we can at least clear up a few misunderstandings concerning trials to date. Professor Aertssen has missed the point that the 2·5 ft. wave height quoted for sea state 5 refers to the quarter-scale situation appropriate to trials of the Rx craft. The corresponding full-scale wave height is 10 ft. Mr. Long comments on the lateral acceleration of 0·15 g which occurred between 45 and 55 knots in calm water due to intermittent ventilation associated with the outboard pods. This was uncomfortable to personnel standing about in the wheelhouse, not 'strapped into aircraft type seats' as he suggests. Such seats are provided for the crew's use under severe weather conditions, but the point we were making is that this flick roll of 1° occurred under calm water conditions, being the one problem spoiling an otherwise motionless ride.

On propellers we cannot offer much guidance to Mr. Crewe because the extent of high speed operations to date provides little data on propeller life. However, we have been impressed with the lasting mirror-like finish on the foilborne propellers made of Inconel 718. Commander Du Cane is understandably puzzled by Fig. 19 which shows a shaft running forward in the outboard foilborne gearbox. In fact, this simply runs to a steady bearing and is integral with the after propeller shaft. He will also be interested to know that the trial runs in excess of 60 knots were made at full load, less 10-15% of fuel consumed. Mr. Buckle's worry about take-off speeds results from 'artistic license' in the commentary on the film. The speeds mentioned in the film were those of the constant speed runs being shown; they do not correspond to the actual take-off speed which, as Mr. Buckle correctly suggests, varies much less with sea state and direction.

We gave much thought to the best manner of discussing and comparing foil system types, and Mr. Silverleaf's method of differentiating between 'surface sensing' and 'motion sensing' systems was a leading contender. In practice, however, beyond the most simple idealistic representation, all systems employ some measure of both surface and motion sensing, and we found it very difficult to separate the influences in a discussion not directed to hydrofoil specialists. The more conventional approach by way of 'platforming' and 'contouring' concepts also suffers from over-simplification, as Mr. Ray correctly points out, but we felt that the real-world compromises are more readily pictured in this representation. Incidentally, a description of HMCS BRAS D'OR's 'motion sensing' control surfaces is given on pages 120 and 121, and they are mentioned on pages 123, 126, 127 and 129. Perhaps Mr. Silverleaf was expecting us to ignore them because he knows that one aspect of our current work is to reassess their need in future craft of this type!

Mr. Ray's spirited defence of the fully-submerged system leaves us somewhat perplexed; we were not aware that it was under attack. Reveiwing the paper, we find only one statement which might reasonably be interpreted as deprecating to the fully-submerged system. On page 129 we state that, 'No system can be truly comfortable in a contouring situation and the fully-submerged foil begins to lose its advantage. The surface-piercing system is expected to have a higher potential ability. The unresolved question is whether the crew will be able to exploit this potential.' By higher potential ability, we mean that the surface-piercing canard system is able to remain foilborne in higher sea states, and we are thinking of wave heights several times the hull clearance, in which a considerable degree of contouring is essential. This ability is simply a function of the reserve lift available in the greater foil area of the surface-piercing system. We agree that this is not a comfortable mode of operation, and one can argue that these extreme conditions will seldom be met, but when they are met the surface-piercing craft will have better reserves of stability to maintain high speed. We speak from personal experience of driving the quarter-scale Rx craft in wave heights exceeding four times its hull clearance in reassuring Mr. Ray that, far from being 'doomed to disappointment', we have already encountered situations demonstrating that beyond a certain sea state, wave height ceases to be a valid criterion for vertical accelerations.

Contrary to Mr. Ray's impression, we were careful to be vague in defining the limits of the practical platforming regime for we do understand the mode of operation he describes, which can be regarded as 'extended platforming' with partial hull contact. We agree that under sea conditions when this is feasible it is a more prudent mode of operation than contouring. What Mr. Ray evidently fails to appreciate is that similar 'gross errors' in the early intuitive concepts of platforming and contouring also apply to the Canadian system. It should be clearly understood that the FHE-400 type of foil system is not a simple contouring device, nor does it follow the idealised 'dry keel' description of intermediate response. The super-ventilating bow foil is insensitive to angle-of-attack changes and the craft damping in pitch is very low. In effect, careful selection of trim and heave characteristics decouples the system from the random seaway in a manner similar to that achieved by the fully-submerged system. We assert that this is achieved in a reliable and consistent manner, regardless of sea state or direction, without any moving elements for the longitudinal modes. We do not claim that this foil system does this as effectively as the fully-submerged foil system. What we do claim is that the surface-piercing system is adequate for the intended military purpose.

In the past, surface-piercing foils have been judged largely on the basis of a tandem configuration dating from World War II, and have been found wanting. Our position is that surface-piercing foils designed on the very different basis of the Canadian system deserve a place in the overall spectrum of high-speed marine vehicles. We are not challenging for the only hydrofoil place in the spectrum and are in no way attempting to deny the place of the fully-submerged foil. We play the role of the defendant, not the prosecuter. We repeat, 'In the present state of the art the important task is to gain a thorough understanding and oceangoing experience of both systems, so that the future designer will have a full repertoire of choices available to him.'

In several places in his discussion Mr. Ray has assumed a criticism that was not implied. Arguments starting with phrases like 'the author's comments appear to be directed toward giving the impression that' cannot be answered when no such direction was intended. We are happy to have him thump his tub on such slender excuses because we acknowledge the virtues of the fully-submerged system for many applications, but he must be careful that he does not 'protest too much', if we recall our Shakespeare.

Mr. Hook and Mr. Long raise the subject of foil retraction which, we repeat, is not a significant problem in our particular application. We wish to point out that non-retracting foils are not an essential requirement of the Canadian system although a retractable version would require a split main foil. It was decided at a very early stage that the weight associated with retraction machinery and the less efficient structural design entailed could more usefully be allocated to fuel or payload. Mr. Long creates a false impression when he talks of a 'specially designed pontoon'. Possibly he is confusing this with the slave-dock that was used to transport the ship from Sorel to Halifax. The pontoon against which the ship is normally berthed is a perfectly ordinary rectangular barge with roller fenders mounted along one side, and it serves only as a spacer. It is true that a squadron of these ships would call for a new approach and schemes for berthing stern to the jetty are contemplated. However, there is nothing magical or difficult about this provided the depth of water is available. It should also be born in mind that retractable foil craft operate only in good weather with the foils up because of impaired metacentric stability in this condition; deep water is still required very close to home.

Commander Du Cane extends our theme of the importance of properly matching vehicle types and roles to the semi-displacement type of craft, and the information he provides is most interesting. Unfortunately we find no reference to the displacement of the ship he describes, nor do we understand his statement that its useful load of 60 tons is 'considerably more than suggested for BRAS D'OR'. Our Table II shows BRAS D'OR's useful load to be 177, 600 lb, which is about 80 tons.

We had originally intended to publish the diagrams presented by Commander Du Cane, thereby adding BRAS D'OR to the data of Ref. 14. We decided that the picture would be misleading because, in the definition of specific power, P is the total installed horsepower which is well in excess of the actual power used in our case. When BRAS D'OR was designed we were faced with the choice of gas turbines in only two ranges of power, about 15, 000 SHP and 30, 000 SHP. We had to install 30, 000 SHP but we do not use it; maximum speed is limited by hydrofoil cavitation, not by engine power. Fortunately, specific fuel consumption of the larger gas turbines is not too sensitive beyond half power and these engines are very light, so that no great disadvantage arises from carrying around this unusable power. Indeed, for an experimental ship this philosophy has an obvious potential advantage, but it does make the comparison presented in Figs. 27 and 28 of dubious value. A better picture could be obtained by using the maximum continuous rating of the engine (22, 000 SHP) which has never been exceeded on trials. This would give a specific power value (P/WV) of 1·8 and reverse the power comparison with Commander Du Cane's ship. We believe that the data point in Fig. 27 located vertically below the point labelled BRAS D'OR is Mr. Silverleaf's own estimate for BRAS D'OR, made on this more valid basis.

This also applies to Mr. Crewe's comment on our apparent high power-to-weight ratio, compared with that of the SR. N4 hovercraft. On the basis of maximum continuous power we have 104 SHP/ton, still about 30% higher than SR. N4 but, we submit, an appropriate differential for an experimental naval craft compared with an operational commercial vehicle.

In connection with Fig. 29, the point Commander Du Cane has labelled BRAS D'OR represents the design condition of 50 knots in sea state 5. As mentioned in the paper, Rx trials have shown that this same speed can be maintained out to wave height values of at least $h/W^{1/3} = 4{\cdot}75$, so that this spot should really be a horizontal line extending off the diagram to the right. In Fig. 30, the vertical acceleration value should be reduced to 0·25 g (r.m.s.) in line with the quarter-scale trial results mentioned in the paper.

These discrepancies in no way detract from the importance of Commander Du Cane's main point, also made by Mr. Vosper, that careful comparison is necessary to find the proper place for hydrofoils relative to more conventional craft. Taking up Mr. Vosper's comments, we would certainly agree that a weight penalty is being paid for high speed, but we find the way he puts it somewhat misleading. He implies that the useful load is reduced by the weight of the foil system, which in BRAS D'OR is 18·6% of the displacement. However both the hull and the machinery of a conventional semi-displacement craft designed to do the same job would be considerably heavier and in practice the overall useful load ratio of hydrofoils need not be all that different. We take the view that some extra penalty is acceptable for the additional seakeeping ability of the hydrofoil; the major penalty for speed is paid by all types of high speed vehicle. Relating these ideas to true quantitative values of cost-effectiveness is a task beyond our present capabilities, as we are sure Mr. Vosper well understands.

Turning to Mr. Siverleaf's first question, it is always difficult to isolate reasons for specific costs, and undoubtedly the attempt to achieve a high payload ratio in BRAS D'OR has not been cheap. It has led to the exacting standards of engineering design and manufacturing referred to by Mr. Long. However, the greatest influence on cost has been the attempt to achieve this at a speed as high as 60 knots. We are paying very dearly for the last few knots, and to achieve a comparable payload ratio at a maximum speed of 50 knots would not be difficult or unreasonable. Regarding automatic control systems, Mr. Silverleaf is correct if he is suggesting that the electronic control unit itself would add little to the total cost of craft of reasonable size. However, at the 200 ton size we are pushing the state of the hydraulics art and the development of high powered actuators having the required response characteristics has proved to be a major undertaking.

Mr. Silverleaf points out that the discussion of future prospects is slanted towards naval applications and that many of the arguments may not apply in commercial roles. One of us made precisely the opposite comment when discussing Ref. 14, so he knows that his point is well taken. Our hope is that a good balance has now been struck. More detailed comparisons and analysis of the relative merits of the various types of hydrofoils, hovercraft and semi-displacement craft should await further sea trials experience, in our view. The general feeling that has developed against surface-piercing hydrofoils is evidence of the danger of drawing premature conclusions. There is an equal danger of overselling a particular type of craft in roles to which it is not well suited, and in view of Mr. Ray's comments we wish to make it quite clear that this is not our intention. BRAS D'OR was designed to a specific role and we believe the choice of features to be well founded for that role. Beyond that, we submit that our experience vindicates the modern surface-piercing hydrofoil as a contender for other roles, but we certainly do not advocate a commercial version of BRAS D'OR herself.

To the final question posed by Mr. Silverleaf, 'Is the air-water interface the best place for really high speeds?', we would answer with a definite 'No'. It is certainly not the best, but in naval applications one cannot always choose the best and there are sound reasons for requiring high speeds on the surface. To what extent the same can be said of commercial applications is, in our view, a much more difficult question, and one we do not have the experience to answer.