Canadian Advances in Surface-Piercing Hydrofoils

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The surface-piercing hydrofoil system exemplified by HMCS *Bras d'Or* is a unique development which appears to combine some characteristics of other contemporary designs but, in fact, is derived from an early concept of F. W. Baldwin and Alexander Graham Bell. Essential features of this concept are compared with those of other surface-piercing systems in a review of today's state of the art. Lessons learned from trials at sea have been incorporated in design studies of possible follow-on naval hydrofoil ships. Highlights from this continuing exploration indicate good prospects, based on important advances in key areas of design, for high performance with good seakeeping and cost benefits.

Introduction

THE ability of a 200-ton surface-piercing hydrofoil HMCS *Bras d'Or*[1] to operate in the open ocean at high speed and with the seakeeping characteristics of a 3000-ton conventional ship has been clearly demonstrated.[2] Moreover, studies based on the results of these trials have indicated that it is feasible to design simpler hydrofoil ships capable of undertaking a wide range of duties currently assigned to much larger warships.

Since *Bras d'Or* represents a distinct advance over earlier surface-piercing hydrofoil concepts, the time is appropriate to take stock of this Canadian development, which has been running in parallel with and deliberately complementary to the development of fully-submerged hydrofoils in the USN. Figure 1 shows how *Bras d'Or* is related in size to the major USN hydrofoils *Highpoint* and *Plainview*.

The three basic surface-piercing concepts will first be reviewed. It will be seen that the Canadian system attempts to borrow good features of each, but breaks new ground in its use of a superventilated foil at the bow. By this combination of features, a seakeeping ability has been achieved more comparable with that of contemporary fully-submerged systems than with the earlier surface-piercing concepts.

In some ways, *Bras d'Or* herself is not completely typical of the concept. Her design was heavily influenced by operational needs for a) an unusually wide speed range between takeoff at about 20 knots and maximum speed of 60 knots, and b) exceptional endurance and seakeeping qualities in the hullborne patrol mode at 12 knots.

Subsequent design studies have not been subject to these constraints and the final part of the paper outlines how the lessons learned from *Bras d'Or* might be applied to more general-purpose hydrofoil warships. Exploiting the special characteristics of surface-piercing foils, such ships could be complementary to the types best evolved from current development of fully-submerged foil systems.

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Index categories: Surface Vessel Systems; Marine Vessel Design (Including Loads); Marine System Testing.

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Basic Surface Piercing Systems

Bell-Baldwin Ladder Principle

The earliest successful hydrofoil craft used "ladders" of fixed foils arranged so that variation of the foil area immersed provided the required altitude stabilization. As will be clear from Fig. 2, which shows the original Bell-Baldwin HD4, 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 the foil system, having no moving parts and no controls, is inherently simple and reliable.

The ladder system is attractive because of its large number of short-span foils. This permits the designer to optimize foil section shape at various points up the ladder, starting at the bottom with thin high-speed sections. This freedom given the designer to vary foil unit geometry with speed, including the basic variation of foil area, permits the speed range between takeoff and maximum to be significantly greater than with fully-submerged foils. Maximum speeds can be three times the takeoff speed, compared with a factor typically less than two for fully-submerged foils.

The major disadvantage is that ladder foil units tend to have a very stiff response at high speed in rough water, leading to a rough ride. If the dynamic response is opti-

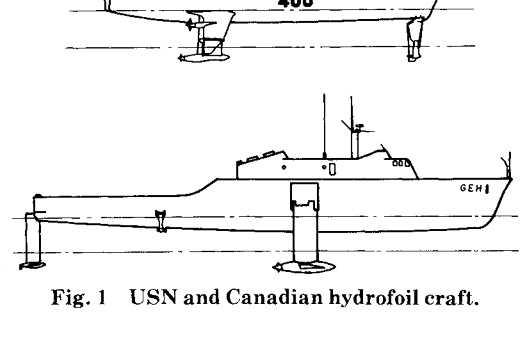


Fig. 1 USN and Canadian hydrofoil craft.

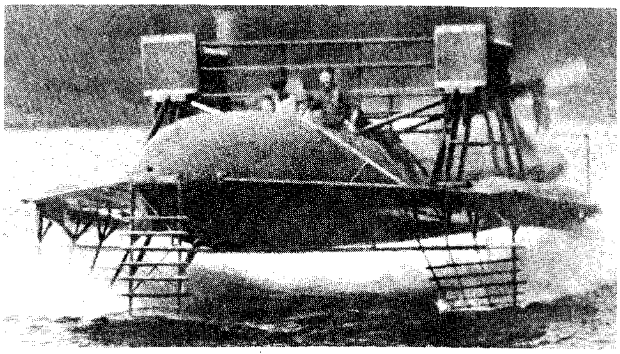


Fig. 2 Bell-Baldwin HD-4 (Photo by G. Grosvenor).

mized at maximum speed, the wide foilborne speed range can make it difficult to provide adequate stability near takeoff speed. Mutual interference or "biplane" effects also detract from the efficiency of these units.

Development of the Bell-Baldwin system during the 1950's has been documented by Crewe[3] and Eames.[4] Future applications of this system are likely to be restricted to special situations demanding a fully-contouring type of response, in which the large lift available in the reserve foil area may be called into play. For example, small unmanned boats of this type were used by the Canadian army to lay smoke screens along beaches. The essential needs were high speed and large stability margins for operating in waves which might approach the boat's length in height.

Supramar Dihedral Foils

The original Schertel-Sachsenberg system of World War II was the logical development of surface-piercing foils to a monoplane type of construction, using V dihedral foils to obtain the required change of area. The earlier boats such as VS-6 and VS-8 had almost identical surface-piercing foils forward and aft, in nonsplit tandem configuration. As Supramar have developed the concept over the years through the PT-10 to the PT-150, the geometrical differences between forward and after foils have increased. Less surface-piercing area has been used aft, until the after foil has become fully submerged in the PT-150.

This evolution is in keeping with the Canadian concept for optimizing the ratio of stiffness to damping for each foil unit. However, Supramar have retained a tandem configuration justified on grounds of structural simplicity, LCG tolerance, and convenience of hull layout, but believed to be a significant disadvantage hydrodynamically. These boats are inherently stable and satisfactory for use in coastal waters, although their ride is rough in moderate seas and their ability to remain foilborne in following seas leaves something to be desired.

Supramar boats owe their success to their inherent structural and mechanical simplicity, including the use of diesel engines and inclined shafts to conventional propellers.[5] The Supramar system represents an all-a-round compromise, and this has made it acceptable across a wide range of operating conditions; particularly during the early stages of hydrofoil development when designing for a very specific set of requirements would have been risky. Outside Russia they account for about 90% of all hydrofoil craft operating today. There will always be, a future for craft built to this philosophy, and continued evolution of the type is anticipated.

Grunberg-Aquavion Principle

In 1934, Grunberg suggested a novel system in which 10–15% of the craft's weight was supported by a pair of planing floats at the bow, the remainder being carried on a fully-submerged foil aft. The widely-spaced floats were to provide lateral stability but, carrying only a small proportion of the weight, they are inadequate for this purpose in practice. The necessary modification, providing surface-piercing tips to the main foil, forms the basis of the practical Aquavion system.

The Aquavion uses a shape of bow float which also acts as a low aspect-ratio hydrofoil when depressed, and the craft incorporates an additional nonlifting damping plate at the extreme stern. This system is a nonsplit canard by definition, the main foil being of curved hoop form.

Despite the damping provisions, the Aquavion remains essentially a contouring system and its ride is stiff in rough water, made worse by a small hull clearance and low-deadrise hard-chine hull. It has the potential for negotiating high seas, particularly following seas, but incurs the discomfort of increased contouring accelerations. These are kept within reason by the moderate speeds for which Aquavions are designed, typically 30 knots.

In other respects the Aquavion shares the Supramar philosophy of simple structural and mechanical design, with diesel engines and inclined propeller shafts. Perhaps the most promising applications for this type of craft lie in the work-boat field, for transporting crews to offshore drilling rigs, for example. Here, the reliable maintenance of moderately high speeds under all weather conditions is paramount, and comfort standards can be relaxed on occasion to achieve this.

Canadian Surface-Piercing System

The essence of the Canadian development lies in the use of radically different foil characteristics at bow and stern to augment the surface-piercing effect and thus reduce the foil area changes needed to obtain the required response. In this way the over-all 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.

To a first approximation, the lift of a typical foil unit varies linearly with both angle of attack and depth of immersion. One can draw an analogy with a damped vertical spring; the stiffness of the spring is the rate of change of lift with immersed depth, and the damping is the rate of change of lift with angle of attack. Dynamic design is essentially a process of selecting the optimum stiffness and damping of each foil unit, and while this is a greatly oversimplified analogy, it permits a feel for the problem to be developed.

Longitudinal Behavior

Consider the longitudinal behavior of a craft with foils developing equal steady-state lift at bow and stern, as required in the tandem configuration. If the dynamic characteristics are also identical at bow and stern, as shown in Fig. 3a, 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.

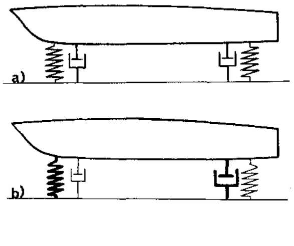


Fig. 3 Longitudinal response: a) Bell-Baldwin; b) DREA concept.

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. This more desirable combination of characteristics is pictured in Fig. 3b.

In rough water, the critical feature is the damping of the bow foil. If this can be made light enough, it will be insensitive to angle-of-attack variations caused by wave orbital velocities. Otherwise the craft will not respond adequately in a following sea. All early surface-piercing craft suffered from this problem, and even the modern Supramar boats have difficulties in moderate-to-heavy following seas.

The lift/drag of a foil unit increases with damping, and decreases with stiffness. Hence the concept pictured in Fig. 3b is calling for inefficient foil units at the bow and efficient foil units at the stern. For this reason there is a very distinct advantage to the extreme canard configuration for surface-piercing systems. With 90% of the load supported on an efficient foil at the stern, considerable license can be taken with the lightly-loaded bow foil to achieve the desired response characteristics, without significantly affecting the over-all lift/drag ratio.

Lateral Stability

In the absence of an automatic-control system, lateral stability is also more critical in surface-piercing systems. Craft which carry most of their weight on a main foil, either at bow or stern, with a small auxiliary unit, normally have a much wider track than tandem craft. Since the roll-restoring moment of a surface-piercing system varies as the square of the track, 90%—10% configurations have a distinct advantage.

The prime requirement is for lateral stiffness, and in the aeroplane configuration 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 early hydrofoil craft were of airplane 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.

This conflict can be resolved by recognizing that stiffness is required only at the ends of a wide main-foil track. A fully-submerged center 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 over-all characteristics required for longitudinal response. Figure 4 illustrates this idea for the nonsplit main foil of a surface-piercing canard.

Configuration and Hull Form

Longitudinal configuration has an important effect on hull design, because of the need to place the center of buoyance at the c.g. without having long lengths of hull overhanging the foils. Notwithstanding *Plainview's* obvious violation of this principle, long bow overhang should be avoided in a rough-water craft to prevent the bow digging into the face of an oncoming wave. More significant than the actual impact is the abrupt forward shift of the center of lateral area, which can lead to directional instability, a craft literally tripping on its nose. Craft with orthodox or airplane configurations therefore require an unconventional bluff-bowed hull, as shown in exaggerated form in Fig. 5.

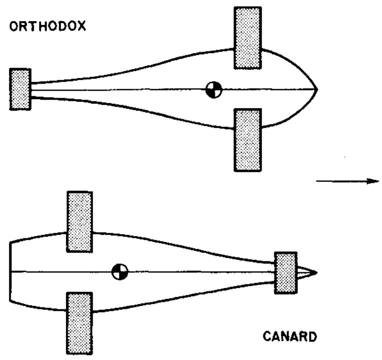


Fig. 5 Longitudinal configurations.

Conversely, the extreme canard configuration demanded by the Canadian hydrofoil system requires a hull with fine forward lines. However, a larger overhang can be tolerated at the stern and the influence on hull shape is seldom as extreme. Proper integration of the foil configuration and hull form is particularly important if extensive hullborne cruising is required. The fine-bowed hull of the canard has clear advantages in both resistance and seakeeping. Moreover, surface-piercing canard foils are ideally suited to the task of damping motions in the hullborne condition because of the large foil areas immersed at slow speed and the long lever arms exerted by the foils in both pitch and roll.

With a surface-piercing system, the takeoff speed is low and the process is a continuous unloading of the hull. These features favor a relatively conventional high-speed displacement hull, rather than one of semiplaning type. From many points of view, therefore, the surface-piercing canard with lightly loaded bow foil is appropriate to hydrofoils in which hullborne cruising behavior is an important requirement.

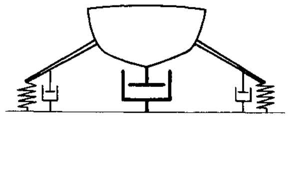
Superventilated Bow Foil

The required combination of stiffness and damping in the bow foil is obtained by using superventilated sections with their greatly reduced lift-curve slope. The analogy between a superventilated foil, which is effectively a submerged planing surface, and the Aquavion type of planing float is interesting. The main difference in principle is that the superventilated foil unit provides the required degree of light damping without resort to a separate plate aft. It also allows the designer more scope in selecting the variation of lift with depth of immersion.

The *Bras d'Or* bow foil is of diamond configuration with a subcavitating center strut and superventilated dihedral and anhedral elements. Tulin Two-Term lower surfaces were chosen for the superventilated sections (Fig. 6) because these appeared to offer the best compromise between hydro-dynamic efficiency and structural strength.

Little information was available on the practical operation of surface-piercing superventilated hydrofoils, so that

Fig. 4 Lateral response.



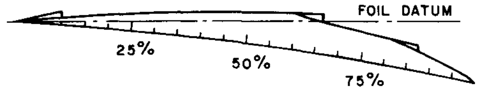


Fig. 6 *Bras d'Or* bow foil section.

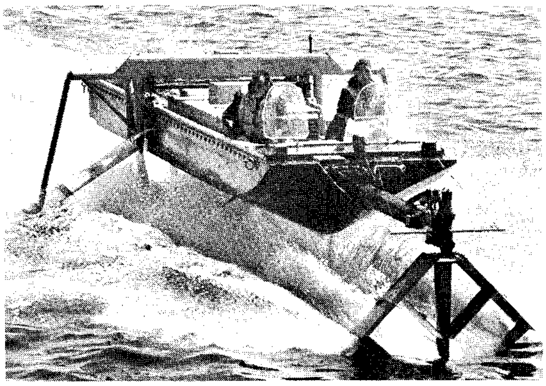


Fig. 7 Rx Foilborne.

extensive experimental development was necessary. Model size had to be as large as practical to minimize scale effects; consequently the bulk of the work was done at quarter-scale, taxing the limits of available towing tank facilities. The same bow foil was also used as part of a complete quarter-scale manned model of the system (Fig. 7). A great strength of the development program lay in the ability to test the same model both in the controlled environment of towing tanks and as a functional unit in realistic seaways.[6]

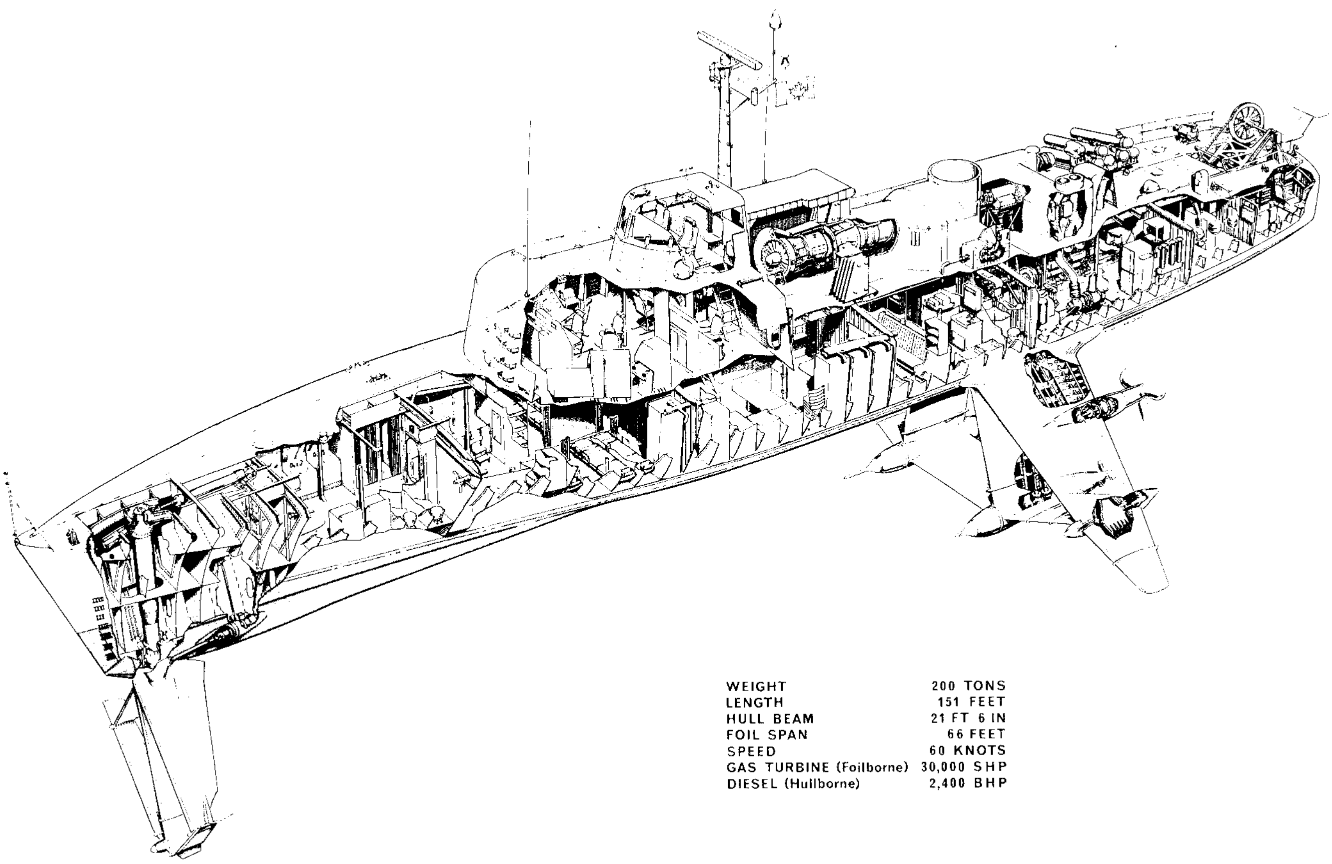
A major concern of the experimental program was upper surface design, with the objective of inhibiting and controlling intermittent flow reattachment. The leading edge was made as fine as practical with a spoiler at 10% chord. To force reattachment to occur in stages and hence reduce the severity of the accompanying lift increases, two additional break points were incorporated into the upper surface, at 66% and 87% chord.

A major problem of the initial manned model trials was that the anhedral foils served as fences to inhibit the spread of ventilation down the dihedrals, leading to cyclic pitching at speeds close to intersection emergence. This was overcome by adding another large upper-surface spoiler to the anhedral sections in the neighborhood of the intersection. Further details of the development of this unique bow foil design have been reported in a contemporary paper.[7]

In summary, contrary to the flexibility allowable with fully-submerged autopilot systems, the requirements of stability and response in rough water dictate the choice of longitudinal and lateral configuration and constrain the characteristics of surface-piercing foil units required for optimum seakeeping. Fundamental to the Canadian concept is the use of a canard configuration with very lightly loaded bow foil. This 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.

HMCS *Bras d'Or*

Figure 8 shows the general arrangement of HMCS *Bras d'Or*, designed to these principles for a specific antisubmarine role. Her duties call for long periods of operation in the open ocean at slow hullborne speeds, and the foil system has been designed to best enhance the seakeeping characteristics of her slender destroyer-like hull. Use is made of the wide speed range available with surface-piercing foils to keep the takeoff speed low, allowing hull design to be optimized for the cruising condition. An unusually large hull clearance is provided in keeping with the open-ocean environment in which the ship is required to operate foilborne. Quite apart from the arguments presented earlier, the requirements imposed by towing and handling variable depth sonar strongly suggest the surface-piercing canard system for the antisubmarine role.



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. 8 HMCS *Bras d'Or*, leading particulars.

The superventilated bow foil carries 10% of the 200-ton weight of the ship and is used as a rudder in both hullborne and foilborne conditions. Its rake can also be adjusted while under way, allowing the optimum angle of attack to be set for the prevailing conditions. It can depress to a negative angle to delay takeoff, enabling the ship to operate within the customary "speed gap" below minimum foilborne speed. Although an inefficient mode of operation, this is a useful operational feature.

The main foil uses delayed-cavitation sections with fences to control ventilation. The efficient fully-submerged center section provides over half the total lift required and heavy damping. The original concept of a foil system with no moving parts was modified late in the design process with the introduction of gyro-controlled anhedral tips. This requirement for augmented lateral stability arose from increasing operational interest in cruising at low foilborne speeds and the exceptionally wide range between takeoff and maximum speeds.

The foil elements are manufactured from 18% nickel maraging steel sheet and forgings with an ultimate tensile strength of 250,000 lb/in^2. This steel is well suited to welding and requires only a low temperature heat treatment without quenching. It is vulnerable to stress-corrosion cracking and hydrogen embrittlement, however, and requires protection from sea water.

The very different speeds and power levels in hullborne and foilborne operation require separate propulsion systems in *Bras d'Or*. For fuel economy at hullborne speeds a 2,000-bhp diesel engine drives two reversible-pitch propellers pod-mounted on the upper main foils. In the foilborne mode a 22,000-shp gas turbine drives two supercavitating propellers pod-mounted on the lower foils.

Table 1 includes leading particulars of HMCS *Bras d'Or*. Eames and Jones[1] have provided a more detailed description.

Sea Trials

Prior to being placed in reserve, the ship completed 648 hr of trials in conditions varying from calm to sea state 7. She was foilborne at speeds from 26–63 knots for approximately 15% of the total accumulated time, and sufficient data was obtained to evaluate key features of performance, stability, seakeeping, reliability, and structural integrity.

Table 1 Comparison of leading particulars

	Bras d'Or (FHE-400)	Possible G.P. design
Normal foilborne Weight, lb	475,000	425,000
Dimensions, ft		
Over-all length	150.75	125
Foil-base length	90	79
Over-all main foil span	66	64
Hull breadth	21.5	25
Hull depth	15.58	14.5
Hullborne draft	23.5	20.5
Hull clearance at 50 knots	8	6.5
Speed, knots		
Maximum foilborne speed		
calm water	60	50
sea state 5	50	45
Hullborne speed		
max. (one engine)	13.75	25
design cruise	12	12
Engines		
Foilborne	1-GT	2-GT
Total SHP (continuous)	22,000	10,000
Hullborne	1-Diesel	...
Total SHP (continuous)	2,000	...
Accommodation		
Normal	20	24
Maximum	25	31

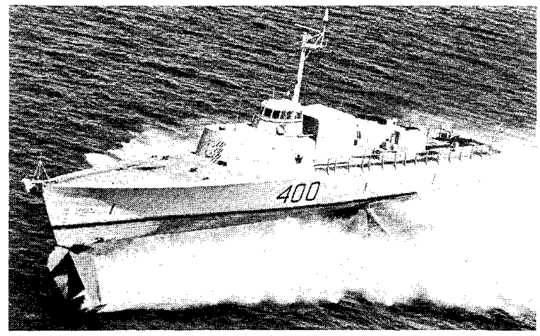


Fig. 9 *Bras d'Or* at 62 knots.

She exceeded her calm-water design speed of 60 knots at full load in 3–4-ft waves (Fig. 9); she took off and landed smoothly, exhibited good stability and control at all speeds, and demonstrated maneuvering characteristics significantly better than predicted. Since sea trials results have recently been published in some detail,[2] the following summary will be confined to the most significant aspects of response and seakeeping.

Of all the results obtained, none were more satisfying than the ship's hullborne seakeeping ability. She operated in seas up to 25 ft with motion characteristics at least as good as those of accompanying 3000-ton destroyer-escorts. Root-mean-square vertical accelerations at 12.5 knots in head sea state 5 were 0.11 g and 0.07 g at the bow and stern, respectively. Corresponding lateral accelerations in beam and quartering seas were 0.06 g in the operations room above the upper deck and 0.03 g at the c.g. Roll and pitch angles were very low in all sea states. Root-mean-square values of roll varied between 1° and 2° while those for pitch were between 1° and 1.5°. The maximum roll recorded was 6.3° in a head sea state 6. In summary, the massive damping effects of the foil system resulted in very smooth hullborne motions in both pitch and roll, with a noticeable lack of slamming at any speed or in direction to the seaway.

During foilborne trials, *Bras d'Or*'s control system was found to be more effective than predicted—a fact which lends support to the possibility of returning to a fully fixed foil system for future ships. In addition to heading hold, the autocontrol system provided roll control using inputs of yaw rate, roll attitude, and roll rate. Trials of this system were carried out at a number of gain settings for each channel and optimum behavior was obtained with roll and yaw rate gains switched off and with roll attitude gain at 32% of the design level. With the autocontrol system switched off completely, the ship was successfully operated through the takeoff and foilborne speed range. This included takeoff, foilborne running at 40 knots and landing under head and following sea state 3 conditions.

Foilborne at about 40 knots in sea state 5, rms vertical accelerations of 0.22 g at bow and stern, and 0.15 g at the

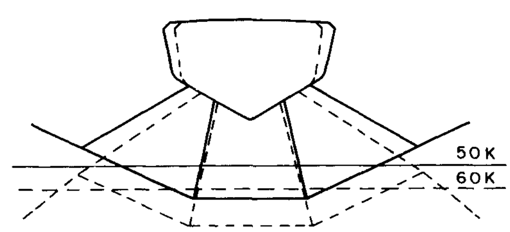


Fig. 10 Main foil for a 50-knot ship.

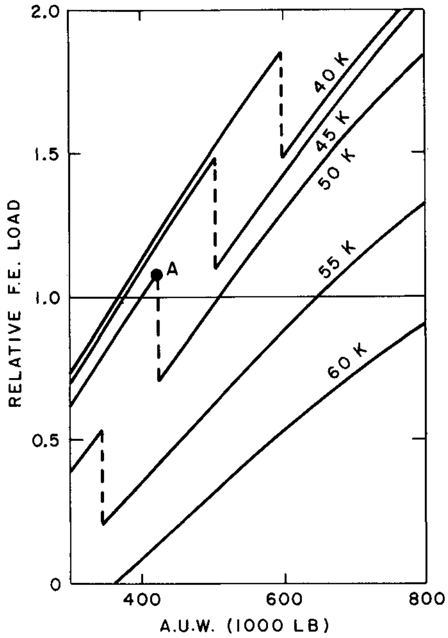


Fig. 11 Parametric performance.

c.g., were obtained in the worst direction to the sea. Corresponding lateral accelerations in beam seas were 0.08 g and 0.05 g in the operations room and at the c.g., respectively. In general, accelerations at 40 knots were only twice those measured at 12.5 knots in the same sea, which is quite a remarkable result for a surface-piercing hydrofoil. The rms roll angle at 40 knots in beam sea state 5 was 2.1° whereas pitch angle increased to 1.5° rms as the ship approached the following sea direction.

Although they were less than 0.1 g, the lateral accelerations were the most annoying to people trying to walk around the ship when foilborne in sea state 5. Because this motion is quite different to anything experienced in a conventional ship, occurring at higher frequencies and with much smaller roll angles, it is hard to make valid comparisons. In total, the sensation was similar to that experienced in an aircraft flying in turbulence. Under operational conditions with proper chairs and seat belts for all personnel closed up, it would set no problem. With extra trials personnel and many visitors, seats were a rare luxury and standing for long periods while foilborne can be very tiring—and not without its moments of excitement.

In summary, the results of sea trials have validated the basic concept and design of *Bras d'Or* as an open-ocean hydrofoil ship. The ability of a 200-ton surface-piercing hydrofoil ship to maintain high speed at least through sea state 5 and to operate hullborne with the seakeeping qualities of a destroyer-escort has been well demonstrated.

New Design Concepts

Over the past two years, a joint DREA-DeHavilland Canada team, has undertaken studies of possible future hydrofoil ships for the Canadian Forces, based on experience with the design, construction, trials, and maintenance of HMCS *Bras d'Or*.

Unforeseen engineering development problems caused *Bras d'Or* to emerge considerably more sophisticated than originally envisaged. That the intended simplicity was not achieved does not detract from the basic concept, which now appears even more attractive in light of possible new roles. But it does call for a careful review of the design philosophy before proceeding with a production version. Fortunately, both the envisaged missions and the engineering simplification desired encourage a more conservative approach and make it possible to proceed with a high degree of confidence.

Bras d'Or trials and concurrent studies indicate that suitably equipped general-purpose hydrofoils could undertake a large number of the duties now performed by destroyer-escorts, with major savings in first cost as well as manning and operating costs. Such ships could also perform a variety of additional useful tasks, including peacetime coast-guard duties such as fisheries protection, search-and-rescue and emergency transportation.

Bras d'Or was designed for good performance in two distinct and widely separated speed regimes, 12 knots for long ocean patrols in the hullborne mode and up to 60 knots foilborne dash to intercept. A more general-purpose hydrofoil requires a balance between payload, range, and speed which is more effective in terms of cost and performance.

Lessons Learned

The major lessons learned have been in the engineering practicalities. To improve reliability, increase structural assurance, and decrease costs to levels considered acceptable for proceeding directly to a production program, retraction from the state-of-art demonstrated in *Bras d'Or* is recommended in two major respects: 1) reduction of the calm-water design speed from 60 to 50 knots; 2) reduction of foil structural design stresses to about 60,000 lb/in.^{2} from 90–100,000 lb/in.^{2}

The most important recommended change concerns the structural design of the foil system; DREA considers improved structural assurance of the foil system mandatory for a production ship. With a 50-knot design speed this can be accomplished within acceptable weight limitations, because cavitation limits will allow an increase in foil thickness, and sufficient hull clearance at a given speed can be obtained with shorter unsupported span

Table 2 Comparative characteristics of hydrofoil systems

		Fully submerged		Surface-piercing	
		Russian	U.S. Navy	Supramar	Canadian
Performance	High maximum speed	x	...	...	x
	Low takeoff speed	...	...	x	x
	Low foil system drag	x	xx	...	...
	High rates of turn	...	xx	...	...
Seakeeping	Comfort in moderate seas	...	xx	x	x
	Ability in heavy seas	...	x	...	x
	Ability in extreme seas	...	...	...	x
	Hullborne seakeeping ability	...	...	x	xx
Other features	For retraction or mooring convenience	x	x	...	...
	Low foil system weight	x	x	...	...
	Capacity for load and C. G. variations	...	...	xx	x
	Engineering simplicity	xx	...	xx	x

[a] Blanks do not imply zero capability; merely that this feature is not noteworthy. Many existing craft do not exploit the full potential of their type.

struts and anhedral foils. The reduced foil design stress would widen the choice of materials. Increased skin thickness, simpler construction techniques involving less welding, and a more easily protected internal configuration would contribute to structural reliability.

In addition to these structural improvements, the reduced speed and strut length make it possible to consider returning to the original concept of a fixed main foil with no moving control surfaces. Experimental verification of this idea will be provided by trials on a 1/3-scale model of a fixed main foil design now being constructed for DREA's new research craft, *Proteus.*[8] Fixed dihedral tips replace the incidence-controlled anhedral tips of *Bras d'Or* in the new design, as shown in Fig. 10. In practice, the addition of aileron flaps may still prove desirable for optimum maneuverability and lateral response, but compared with *Bras d'Or*'s system such controls would demand a fraction of the hydraulic power. The program with *Proteus* will include tests with flaps, and should define the value of such a system.

With a design speed of 50 knots a common propulsion system could be employed for both foilborne and hullborne operation. An internally-mounted twin gas turbine engine arrangement, each engine driving one propeller, would provide more useable deck space, power level versatility, redundancy in case of breakdown, and simplified transmissions. Speeds of 25–30 knots would be possible using only one engine.

Parametric Study

To provide a basis for cost-effectiveness studies, the performance of ships incorporating these simplified design ideas has been calculated over a wide range of size and design speed. Performance was assessed in terms of the weight of fighting equipment that can be carried over a given range at design speeds.

Detailed numerical results cannot be given, but Fig. 11 shows the general trends, which are instructive in themselves. The weight of fighting equipment that can be carried at design speed over the required range is plotted against all-up weight, each curve corresponding to a particular design speed. A relative scale is used, 1.0 corresponding to the load of fighting equipment considered in a particular configuration.

A striking point illustrated by the curves is the penalty paid for design speeds in excess of 50 knots, compared with the minor effect of speed in the 40–50 knot interval. This is due both to large increases in power and to the need to employ separate foilborne and hullborne propulsion systems for design speeds over 50 knots.

The second main point is the considerable advantage offered by the use of twin small engines over a single large installation, as shown by the vertical length of the breaks in the curves. In practice, the redundancy and versatility offered by twin main engines are further important factors in their favor.

Figure 12 shows a hypothetical hydrofoil ship design based on point A of Fig. 11. This ship achieves the required payload-range characteristics with 50-knot maximum speed in calm water, or 45 knots in sea state 5, using twin 5,000-shp engines. Resulting directly from Canadian surface-piercing hydrofoil experience, this design lies well within the established state of art, permitting emphasis to be placed on simplicity, ruggedness, and economy. Although the 425,000-lb all-up weight is very close to the original design weight of *Bras d'Or*, the hypothetical ship has increased payload and its range characteristics are weighted more towards foilborne operations. Table 1 compares the leading particulars of *Bras d'Or* and this hypothetical design.

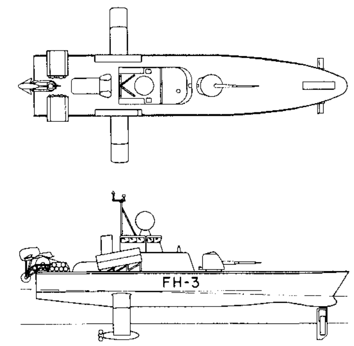


Fig. 12 FH type 3 general arrangement.

Some Comparisons

Seakeeping Regimes

The relative foilborne seakeeping ability of different foil systems remains a controversial subject because the opportunity for valid comparison trials in rough water has not yet occurred. To add the Canadian experience to the pool of semiquantitative knowledge, Fig. 13 is presented, defining four regimes as a function of all-up weight.

Within the *Calm Seas* regime (0–3 ft for a 200-ton ship) the inertia of the craft and damping of the foils prevents significant motions, regardless of the type of foil system. Surface-piercing systems will feel rougher than fully-submerged systems, but the frequencies of encounter are such that a vibration is felt, rather than a motion.

In the *Moderate Seas* regime (3–10 ft for a 200-ton ship) the differences between control systems become most apparent. This regime covers the feasible extent of platforming, and for best platforming a fully-submerged autopilot system is needed. The craft should be controlled to ignore the seas, hence motion-sensing rather than surface-sensing is desirable. Proper selection of damping and stiffness characteristics can give a surface-piercing craft acceptable performance as with *Bras d'Or,* but the ride will be less comfortable than that of an autopilot system; vertical accelerations may be roughly double, although there are no directly comparable data available to confirm this estimate.

This regime extends beyond sea heights equal to the hull clearance. In practice, the forces and motions caused by a hull cutting through wave crests may be less objectionable than those due to contouring in wave heights up to 1.5–2.0 times the hull clearance, depending on hull form. The hull clearance on which this diagram is based is shown by the dotted line.

In the *Heavy Seas* regime (10–20 ft for a 200-ton ship), some degree of contouring has to be accepted and, as this degree increases, the fully-submerged autopilot system begins to lose its advantage. No system can be truly comfortable under such conditions because of the vertical accelerations involved in contouring. Once a high degree of contouring is involved, sea height ceases to be the signifi-

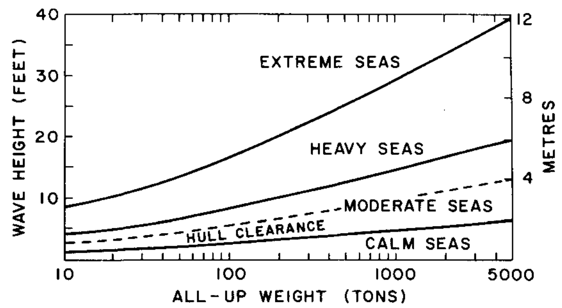


Fig. 13 Seakeeping regimes.

cant criterion, motions being more dependent on wave steepness than height. (This statement is based on quarter-scale trials experience with the Rx craft.[1] The maximum 15-ft seas encountered by *Bras d'Or* while foilborne only border on this condition.)

In the *Extreme Seas* regime (above 20 ft for a 200-ton ship), ability to maintain foilborne operation is the question, and a suitably designed surface-piercing system has the higher potential because of its greater reserves of lift. Whether the crew can fully exploit this potential remains unresolved. The indications from quarter-scale trials, in seas equivalent to 28 ft for *Bras d'Or*, are that such conditions could be tolerated for short duration in the heat of an engagement, but would be unacceptable under routine circumstances.

For Canadian naval purposes, the choice between fully-submerged and surface-piercing foils is strongly swayed by the exceptional hullborne seakeeping offered by the *Bras d'Or* type of foil system. For the tasks envisaged there is no question that habitability is more important under hullborne cruise conditions than for short periods of foilborne operation. Experience with *Bras d'Or* supports the contention that foilborne motions are acceptable for continuous periods of several hours and has confirmed the exceptionally good hullborne behavior of this system. The realities of fuel consumption would limit foilborne runs to a few hours, whereas hullborne patrols may extend over several days.

Types of Craft

It is difficult to predict the potential advantages of the various types of hydrofoil craft, because each is at a different stage in its development. Qualitatively, however, each has certain inherent characteristics, and Table 2 attempts to summarize these, for the four types of craft considered likely to remain in the forefront of development over the next few years.

It is important not to regard this table as a "scoreboard." For example, the Russian system is seen to have the least number of check marks, yet it is undeniably as well matched to its intended function as any other system. A check mark where it is not required would be liability, not an asset, because it would mean that effort had been expended or some compromise made to provide an irrelevant capability.

In summary, the Russian system is unchallenged for high-speed transportation in calm water. The USN autopilot system and the Canadian system are the most advanced developments in fully-submerged and surface-piercing systems, respectively, and roles are foreseen supporting the future developmgnt of both these philosophies. The Supramar system is a simple compromise that does not excel in any specific feature of performance, yet is adequate in many, and it will continue by virtue of its low cost and the wealth of experience gained.

Concluding Remarks

The sea trials of HMCS *Bras d'Or* have validated the basic concept and design of this new type of open-ocean surface-piercing hydrofoil ship. She has operated successfully over a wide range of speed, sea state, and all-up weight, and has met or exceeded all design predictions tested.

Compared with earlier surface-piercing types, the Canadian design principle offers a significant gain in seakeeping ability. As applied to *Bras d'Or*, it is particularly suited to ships requiring a wide range of foilborne speeds, or required to spend long periods at sea in the hullborne mode.

In detailed design, many improvements could be made on *Bras d'Or*. In striving for the best possible performance, the mechanical designers have gone to the limits and perhaps beyond in some respects. In doing so, however, they have established where the system design limits lie, and this in itself is a valuable contribution.

In conclusion, results of the *Bras d'Or* program to date provide confidence that a production program could proceed with low risk, to yield general-purpose hydrofoil ships capable of undertaking many of the duties currently performed by destroyer-escorts.

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