Recent United Kingdom Hovercraft Development

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I. Introduction

DURING the past five or six years, the three largest United Kingdom hovercraft designers/manufacturers have concentrated almost exclusively on developing the present operational hardware designed during the middle to late 1960's and carrying out basic research. The craft currently manufactured by these companies are shown in Table 1. These craft have reached commercial and operational viability by a process of experience and improvement.

Many of the recent developments have been detailed engineering changes leading to improved performance and reliability. Others have been more fundamental in nature, involving, for example, the addition of an extra propulsor (SR.N6.Mk.1S to SR.N6.Mk.6), hull-lengthening (HM.2 Mk.III to HM.2Mk.IV and SR.N4 Mk.1 to SR.N4 Mk.3), and the conversion from water to air propulsion (VT.1 to VT.2). This paper gives a brief review of these developments and of the associated basic research required for them and for the definition of the new hovercraft designs that will extend the present markets by further improvements in economics and increased seakeeping capability.

II. Basic Research

Basic research is necessary to advance the technology of the hovercraft, or air cushion vehicle (A.C.V.), such that its position in relation to other forms of transport is improved. Although the hovercraft, particularly the amphibious type, normally has a significant speed advantage over conventional ships, it is essential to be able to provide this fast alternative for a minimal fare premium. This can be achieved only by improving the efficiency of the hovercraft as much as possible, in particular by reducing the level of installed horsepower.

The main avenues along which research work has been, or is being, directed by the craft manufacturers and their associated component specialists now will be discussed. Recent research has aimed at 1) improving the efficiency of the lift system, 2) reducing craft resistance, 3) improving the efficiency of the propulsor system, 4) reducing craft motion,

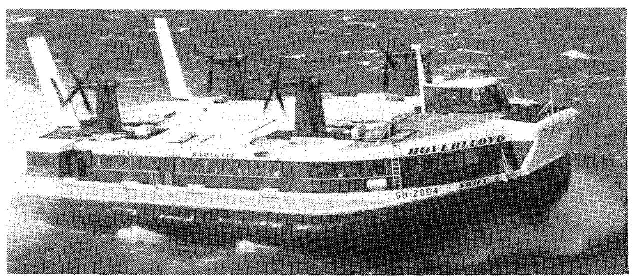

Fig. 1 SR.N4 Mk.2.

Table 1 Description of United Kingdom hovercraft

Manufacturer	Description	Type/class	Max, weight, long tons	Photograph
British Hovercraft Corp. Ltd. (B.H.C.)	Amphibious, air-propelled, peripheral skirted	SR.N4 Mk.2 Mount-batten	200	Fig. 1
		SR.N6 Mk.1S Winchester	13	Fig. 2
		BH.7 Mk.5 Wellington	54	Fig. 3
Vosper Thornycroft Ltd. (V.T.L.)	Semiamphibious, marine-propelled and amphibious, air-propelled, peripheral skirted	VT.1 and VT.2	90	Fig. 4
Hovermarine Transport Ltd. (H.T.L.)	Nonamphibious, marine-propelled, sidewall	HM.2 Mk.III	20	Fig. 5

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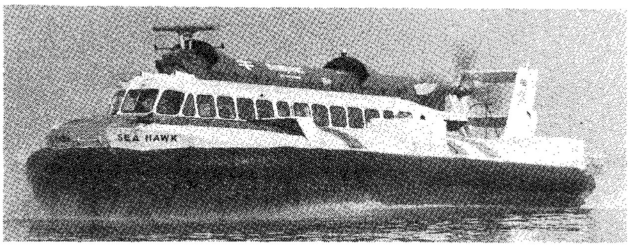

Fig. 2 SR.N6 Mk.1.S.

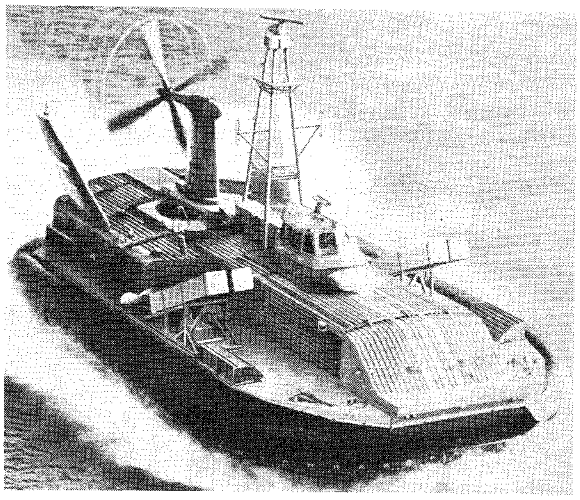

Fig. 3 BH.7 Mk.5 fitted with missiles.

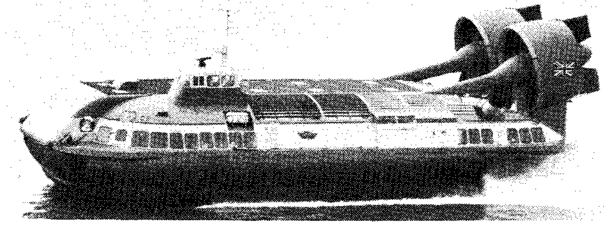

Fig. 4 Vosper Thornycroft VT.2.

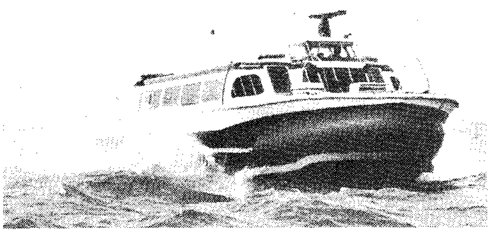

Fig. 5 Hovermarine HM2 Mk.III.

1	LIP SHAPING	–	LARGE RADIUS REQUIRED FOR SMOOTH ENTRY OF AIR
2	AREA DISTRIBUTION IN DUCTS	–	AVOIDANCE OF DISCONTINUITIES
3	SIZE AND SHAPING OF CENTRE BODY	–	MINIMAL BLOCKAGE CONSISTENT WITH MECHANICAL CONSTRAINTS
4	FAN/INTAKE JOINT	–	AVOIDANCE OF FLOW BREAKAWAY AND LEAKAGE OF PRESSURISED AIR
5	HEIGHT	–	COMPROMISE BETWEEN EFFICIENCY CONSIDERATIONS AND BASIC CRAFT
6	PROPELLER AND PYLON INTERFERENCE	–	UNAVOIDABLE WITH THIS CONFIGURATION

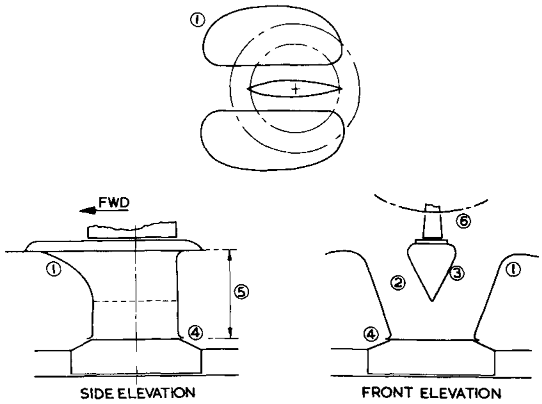

Fig. 6 Problem areas associated with the split nostril fan intake.

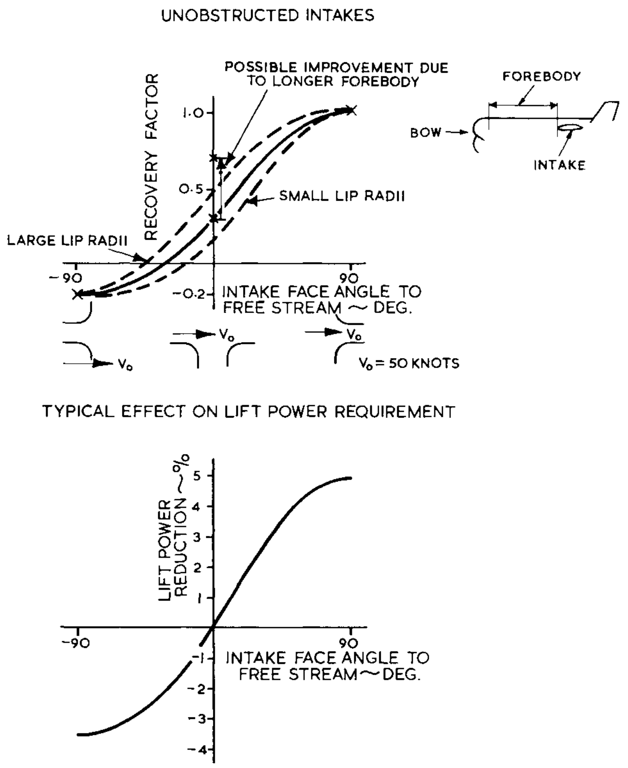

Fig. 7 Variation of intake efficiency with intake attitude.

and 5) improving engine air filtration. There is, of course, considerable cross-coupling between these requirements, particularly in the area of skirt design.

A. Lift System

The lift system, which may be taken to include the fan, the internal ducting, and the flexible skirt, is an area where there is considerable scope for efficiency improvement. This is particularly the case for the current amphibians fitted with bag/finger skirts which require about 25–30 hp for lift for each ton of all-up weight and achieve an overall lift efficiency of approximately 30% in terms of cushion power generation.

The three main, roughly equal, sources of power loss are in the fan intake, in the plenum, and across the feed holes through which the air is passed from the upper bag to the cushion. During the past year, B.H.C. has been actively investigating ways of reducing lift power, with a target level of 50% in view.

Figure 6 shows diagrammatic illustrations of problem areas associated with a typical B.H.C. split intake. These intakes are required to operate over a wide range of sideslip angles, but they are biased in the forward direction. Figure 7 indicates that change of intake face attitude can reduce lift power by up to 5%. The order of pressure loss associated with the duct

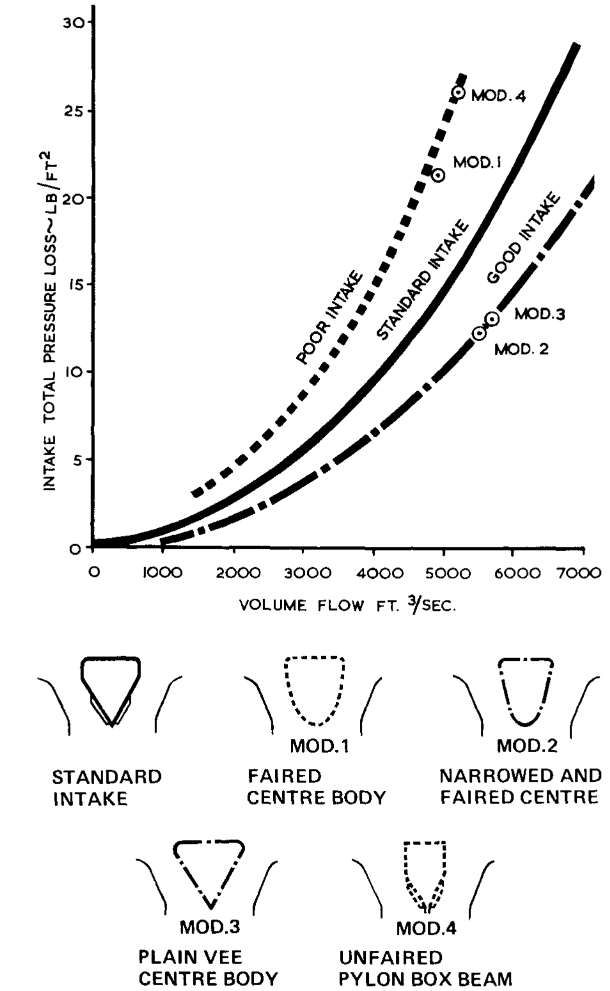

Fig. 8 Effect of centerbody shaping on the performance of BH.7 split nostril intake.

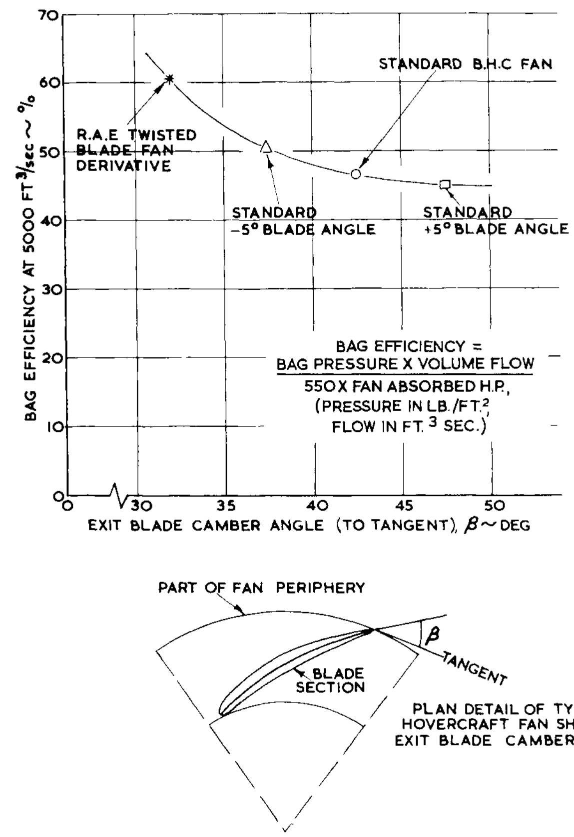

Fig. 9 Bag efficiency variations with fan geometry.

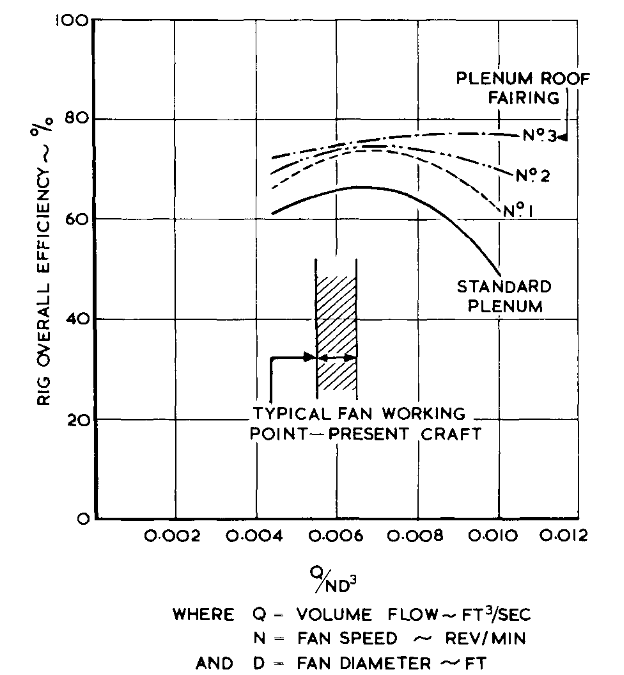

Fig. 10 Variation of fan rig efficiency with volume flow coefficient and plenum roof shape.

shaping in present B.H.C. nostril intakes is shown in Fig. 8. Intake pressure loss can be reduced by some 30% with improved duct design.

Recent work on fan installations on a model BH.7, aimed at evaluating the effects of twisted fan blades, has suggested that changing fan blade angle can improve overall system efficiency without necessarily implying a higher fan efficiency. This is attributed to better matching of the air swirl angle at entry to the plenum diffuser to the diffuser requirements. The variation of bag inflation efficiency with fan blade angle, given in Fig. 9, shows a possible gain of some 30% over present B.H.C. fan installations.

Further investigation of diffusion effects has concentrated on shaping the diffusion path, i.e., diffuser depth, to match the air discharge angle from a fixed blade fan and to control the rate of diffusion downstream. Significant improvements, in excess of 10%, in maximum efficiency as measured at discharge from a circular diffusion chamber were obtained, as shown in Fig. 10, but, more significantly, the most successful design (No. 3) substantially extended the range of flow over which high efficiency was measured.

The loss across the bag cushion feed holes can be reduced by reducing bag-to-cushion pressure ratio, as illustrated in Fig. 11. The extent to which pressure ratio can be reduced toward unity is dependent upon considerations of roll stability and motion in waves as related to the stability of the skirt geometry. Full advantage of the Fig. 11 improvements probably would require gearing or fan design changes in an integrated system. The changes of craft and skirt geometry in developing the SR.N4 are permitting some of this improvement without gearing or fan changes. In current B.H.C. designs, some 20% of the lift power is required to pump the cushion air through the cushion feed holes. With bag-to-cushion pressure ratios reduced to the order of 1.1, the power requirement can be reduced to below 5%.

One obvious and extremely effective means of lift power reduction is to reduce the air volume flow, as demonstrated in Fig. 12. The target reduction in lift power of 50% can be achieved with a one-third reduction in volume flow. The

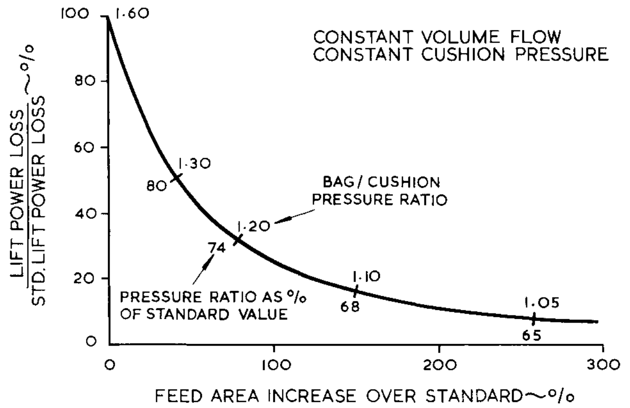

Fig. 11 Typical reduction of lift power loss and associated bag/cushion pressure ratio with increased feed hole area.

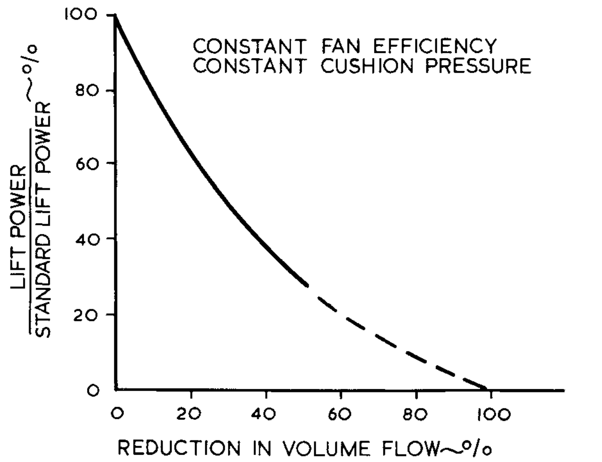

Fig. 12 Typical reduction of lift power with reduction of volume flow.

extent to which this can be used to reduce total power requirement clearly will depend upon suitable skirt design, which avoids undue resistance increase. Present B.H.C. designs can be improved to a significant degree in respect to cushion volume flow by improvements in cushion sealing at the stern. This is a difficult detail design problem, which is receiving a great deal of attention in the lengthened SR.N4 design.

B. Resistance and Associated Skirt Geometry Features

Reduction of resistance is clearly a source of efficiency improvement, and advances can be made on several fronts.

1. Aerodynamic Components

These are the body profile and intake momentum terms. For a typical standard SR.N4 operating in average English Channel conditions of 4-ft significant seas at 45 knots waterspeed, the aerodynamic components with a headwind component of 10 knots represent over 35% of the total resistance, half of which arises from cushion flow momentum resistance. The latter is a direct function of the fan air volume flow and will be reduced in proportion to any airflow savings made in the lift system.

Reductions in body profile resistance can be achieved by paying attention to detail shaping and general "cleaning up" of the craft exterior. Tests carried out at B.H.C. and at the Cranfield Institute of Technology have shown that significant reductions below typical current levels are possible (e.g., as illustrated in Ref. 1, up to 30% reduction appears possible for SR.N4). In addition to improving the zero yaw profile resistance, attention must be given to the shape of the aerodynamic force curves with yaw angle variation, in relation to overall craft handling characteristics. Figure 13

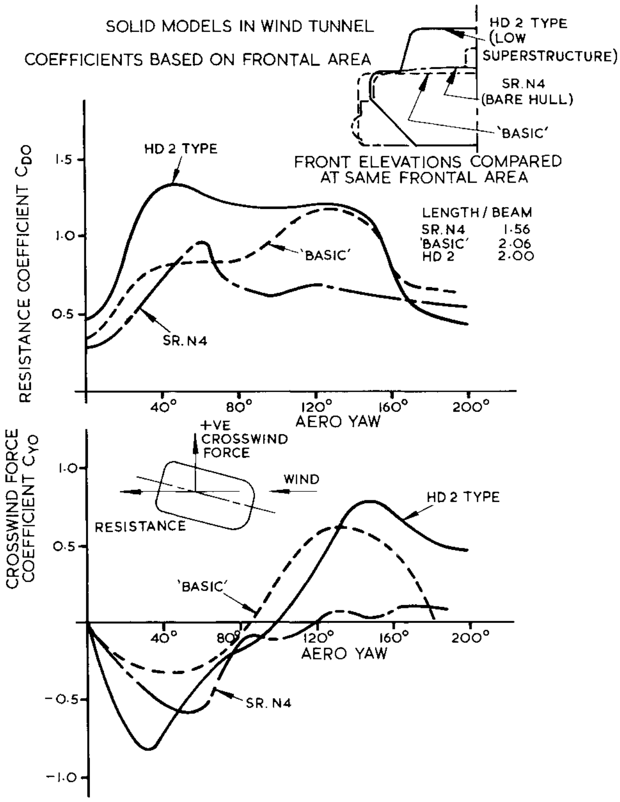

Fig. 13 Aerodynamic resistance and crosswind force.

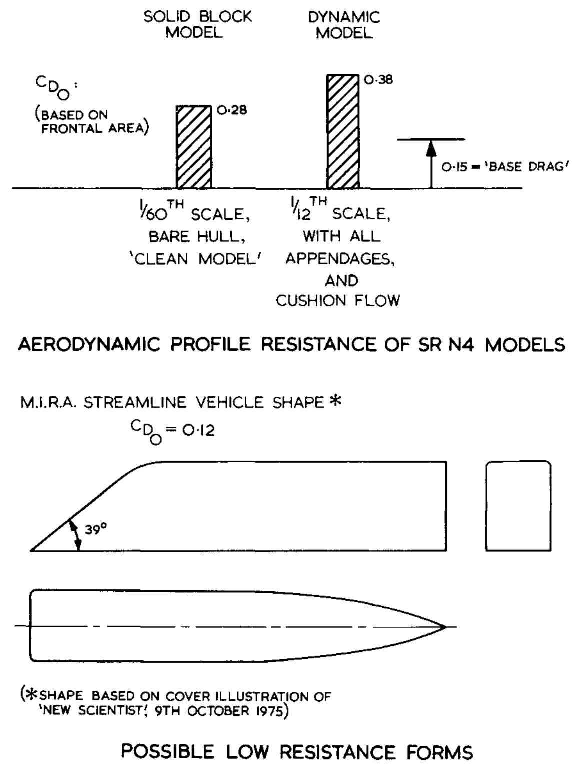

Fig. 14 Aerodynamic profile resistance.

illustrates different curve forms measured for various block models.

The adoption of more streamlined forms could lead to larger savings, possibly at the expense of effective payload area with extreme shaping. Thus, Fig. 14 shows typical measured SR.N4 resistance coefficients based on frontal area to be in the range 0.28 to 0.38, with an estimated 0.15 of this due to base drag. A total drag coefficient as low as 0.12 has

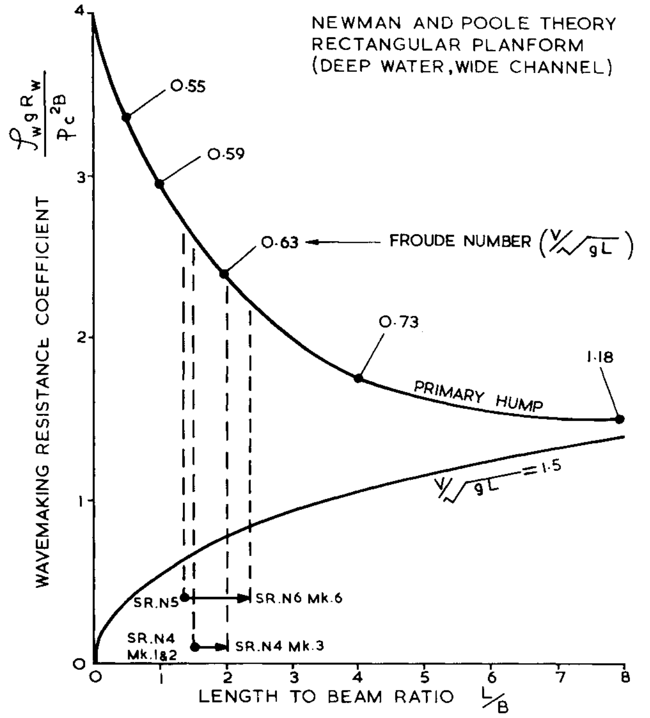

Fig. 15 Predicted wavemaking resistance; variation with length/beam.

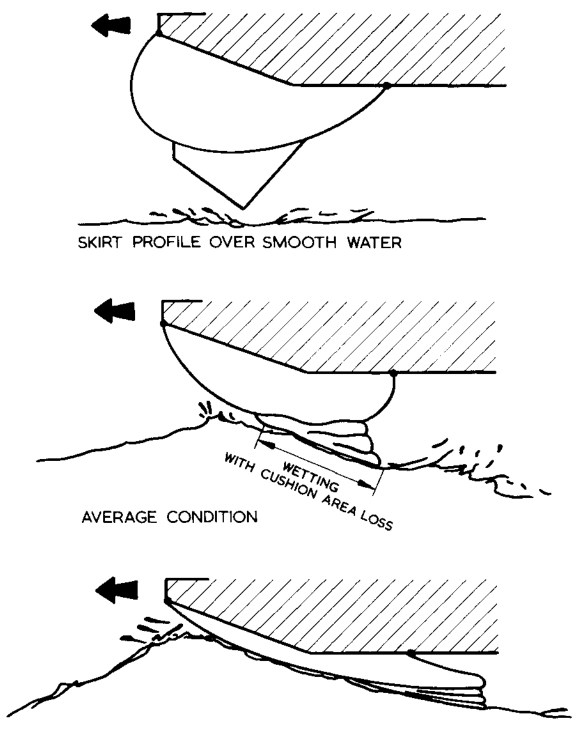

Fig. 16 Skirt behavior: existing system.

been quoted for a vehicle shape developed by the Motor Industry Research Association (M.I.R.A.), as illustrated in Fig. 14.

2. Hydrodynamic Components

These comprise the wavemaking resistance, together with water "wetting" and motion-induced resistance when over water. Of the 65% of total resistance represented for the typical SR.N4 case, only about 1/6 is associated with the basic pressure area wavemaking, since the waterspeed is about twice

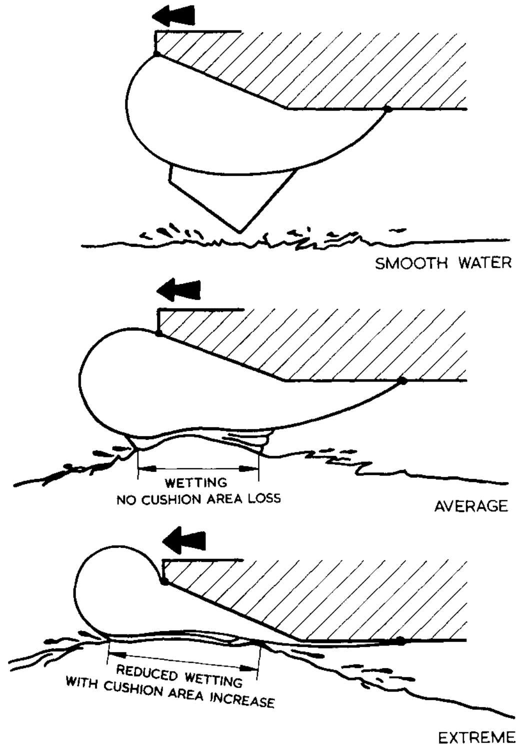

Fig. 17 Skirt behavior: improved response.

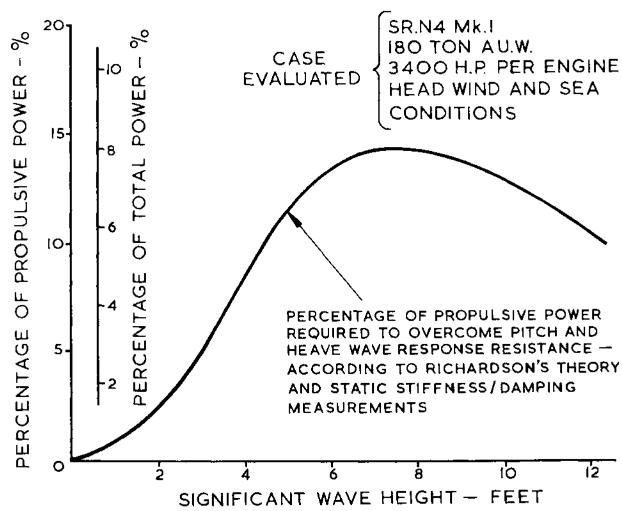

Fig. 18 Power increment due to response to waves.

the primary hump speed. Its relative importance can increase for other craft design concepts if low Froude number or high cushion pressure (p_c) are required. The ability to negotiate the hump of wavemaking resistance is, however, of obvious importance. Figure 15 summarizes the resistance coefficient variation according to Ref. 2 with cushion length-to-beam (L/B) ratio, at primary hump and at a typical cruise condition. The saving in primary hump wavemaking resistance (R_W) is shown for the current lengthening development of B.H.C. craft. The development of craft with higher L/B ratios must be tempered with the provision of adequate roll stability, not forgetting the increase in craft resistance at operating speed when the hump has been negotiated.

In the case of sidewall craft, geometric changes of the sidewalls can make a significant difference in the wavemaking resistance. Considerable model testing by Hovermarine now has developed optimized hydrodynamic features with potential improvements in performance which are associated with a 20% total resistance reduction under cruise conditions.

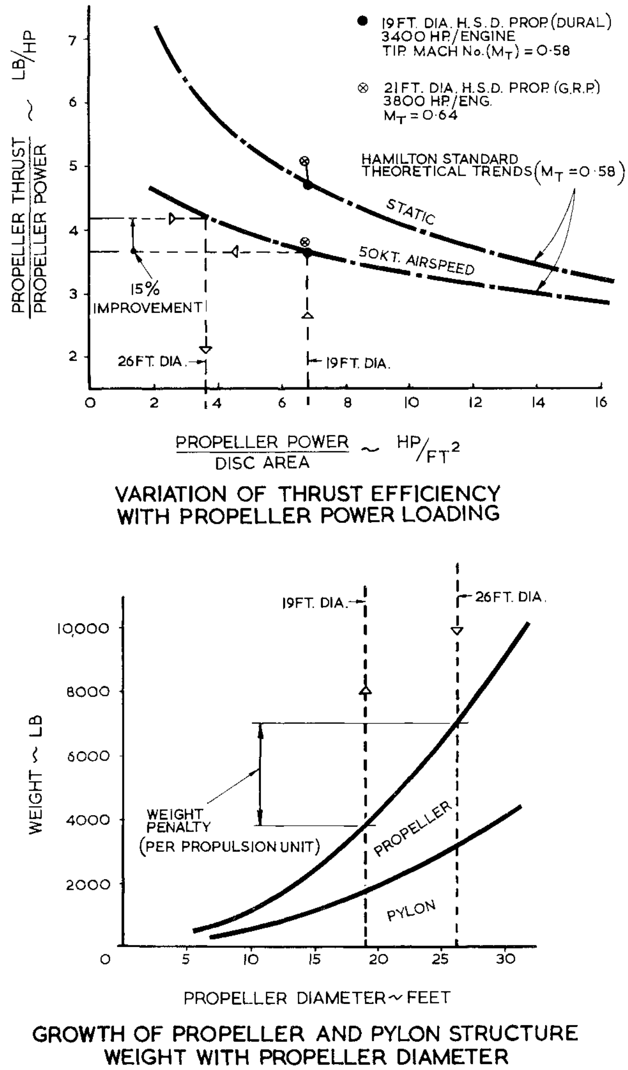

Fig. 19 Improvement of thrust efficiency.

The remaining major part of the hydrodynamic resistance is related directly to the characteristics of the flexible skirt. In general, the better the skirt's ability to respond to the wave profile, the lower will be the resistance. Figures 16 and 17 illustrate diagrammatically what are considered to be poor and good skirt system behavior. Current B.H.C. developments are aimed at achieving good response, in association with the lift efficiency improvement of low bag to cushion pressure. That part of this resistance which may be attributed directly to the response of the craft to waves has been studied theoretically in Ref. 3. Its relative magnitude is summarized in Fig. 18 for typical SR.N4 conditions.

The skirt, being a new branch of engineering peculiar to the hovercraft, naturally has been the subject of a great deal of research and development effort and, as far as British amphibious craft are concerned, has been centered on the B.H.C. bag/finger type and the HDL/Vosper Thornycroft loop/segment type. The development histories of these skirts already have been well documented elsewhere (e.g., Refs. 4 and 5), but essentially the two types reflect differing viewpoints on the relative importance of craft stability and behavior in waves, power consumption, and flexibility, and each has its merits in certain respects. For example, in relation to the power reduction target referred to previously, the uncompartmented loop/segment skirt as on VT.2 already incorporates the desired low bag/cushion pressure ratio characteristic.

Recent advances with the bag/finger skirt have included the introduction of the tapered skirt and an improved responsive rear skirt configuration for the SR.N4. The basic philosophy behind the tapered skirt is that it is a way of obtaining a deeper cushion while minimizing the increase in overall c.g. height and skirt weight, thus offering improved performance and protection in waves. The benefits to be gained from substantially deeper cushions have been studied at model scale by both B.H.C. and V.T.L. This work has indicated that a marked reduction of resistance is possible in high sea states.

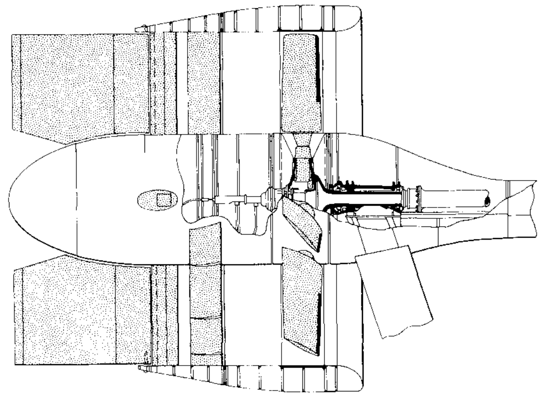
Fig. 20 VT2 propulsor unit.

Rear skirt configurations also have received considerable attention, being a significant source of air leakage and consequent loss of efficiency. It has, however, been difficult to evolve a completely satisfactory form of rear skirt which effectively seals the cushion at the rear and at the same time does not lead to excessive water scooping with an associated increase in drag and craft directional stability.

Attempts at B.H.C. to measure the wetting resistance of the various skirt components of amphibious designs have been relatively unsuccessful to date, but experiments are continuing. The effect on resistance and motion of introducing or removing cushion internal division in both B.H.C. and V.T.L. configurations also has been examined in dynamic model testing and is still the subject of continuous appraisal. The relative merit of transverse cushion division has been found to vary with operating speed/wave condition and with peripheral skirt configuration, particularly the rear-end design.

From the foregoing, it appears that a possible solution to the power-reduction problem can be found from an attempt to combine the favorable characteristics of the exisiting skirt types. However, it is far more likely that a new type of system must be developed to achieve the power reductions required.

C. Propulsion System

Propulsor research has encompassed types using both air and water as the working medium, although the majority has been concerned with air-propulsion systems suitable for the amphibious type of hovercraft. As this is a highly specialized field, the two major propeller manufacturers in the United Kingdom, Dowty Rotol Ltd. and Hawker Siddeley Dynamics Ltd. (H.S.D.), have been responsible for most of the research and development.

1. Free Air Propellers

Dowty Rotol, in conjunction with the Aircraft Research Association at Bedford, have been examining the application of "supercritical" aerofoil sections to propeller design. Such developments could increase thrust, or alternatively reduce blade size and weight for the same thrust, and are expected to be particularly beneficial in the design of relatively slow-running propellers, which is fortunate in view of the current emphasis on noise reductions.

The propellers are known to be a major source of hovercraft noise, and there has been increasing pressure to develop units capable of producing the required thrust at considerably

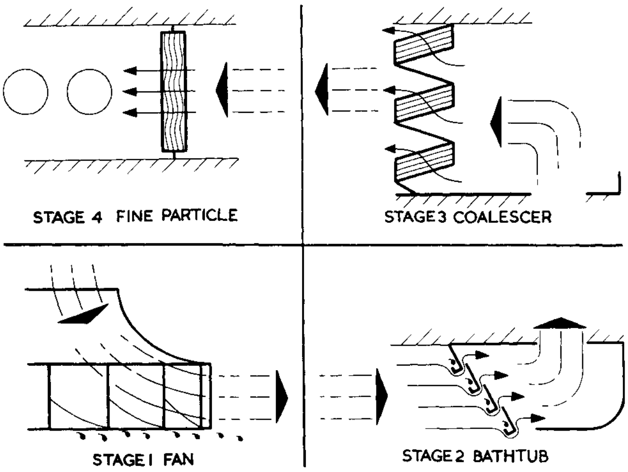

Fig. 21 Four-stage engine air filtration.

lower tip speeds. Those produced by Dowty Rotol for the SR.N6 Mk.6 represent a considerable advance, operating at much-reduced tip speed compared with those on a standard SR.N6 (see Sec. III.A.1.b).

Thrust efficiency can be increased by reducing disk loading at the expense of propeller and associated structure weight. This is illustrated in Fig. 19, where, for typical SR.N4 and BH.7 applications, a 15% improvement in the thrust at 50 knots airspeed would imply a weight penalty of about 1½ tons/propulsion unit for the required propeller diameter change from 19 to 26 ft. As also noted on Fig. 19, the current development using the H.S.D. 21-ft-diam propeller has achieved a 4% efficiency improvement at the expense of some tip speed increase (tip Mach number increased from 0.58 to 0.64). Some of the weight growth also has been avoided in changing from dural to glass-reinforced plastic (GRP). The propeller weights shown on Fig. 19 are considered to be high relative to the latest H.S.D. forecasts for aluminum alloy propellers and of the order of twice those for composite GRP/metal spar construction.

2. Ducted Air Propulsors

In addition to developing slower-running free propellers to combat the noise problem, Dowty Rotol have been engaged in the design and manufacture of multiblade axial ducted fan units and were responsible for the fans fitted to the VT.2 (see Fig. 20 and Sec. III.B.2). The advantages of this type of propulsor over the free propeller may be summarized as follows: 1) a significant increase in static thrust, 2) a reduction in noise level due to a lower operating tip speed and the beneficial effect of the duct, and 3) the duct offers some protection to personnel.

These advantages have to be set against an increase in weight and complexity, and careful design of the duct is necessary to avoid problems of distortion and loss of thrust in reverse pitch. The ducts on the VT.2 incorporate a plastic foam inner lining to maintain a close rotor tip clearance, and the section profile was modified to give a larger trailing edge radius to improve the reverse thrust characteristics.

The other major propeller manufactuers, Hawker Siddeley Dynamics, do not believe that a multiblade configuration is necessary for hovercraft applications and suggest that a four-bladed unit is to be preferred, thus reducing the weight penalty and possibly easing the reverse pitch problem. This is essentially a shrouded propeller unit rather than a ducted fan and is similar in concept to the experimental modification applied by Air Vehicles Ltd. to an SR.N6 (see Sec. III.A).

3. Water Propulsion

Although some research has been carried out on water propulsion systems, the relatively small number of nonamphibious hovercraft designs that have been produced in the United Kingdom has not as yet justified any major expenditure.

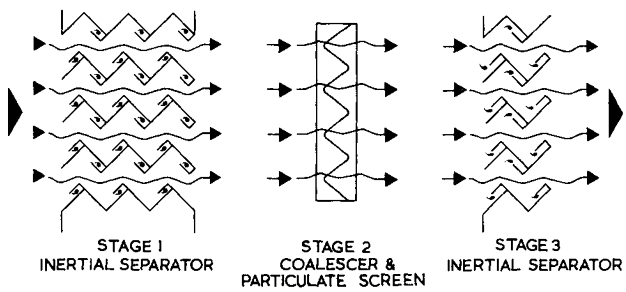

Fig. 22 Three-stage engine air filtration.

D. Engine Filtration

Separation of salt spray from the intake air has been a significant problem from the time that the first gas turbine engine was fitted to the SR.N1 in May 1960. The target over the past 16 years has been to reduce the salt/air ratio by weight to 0.01 ppm. The current level of less than 0.02 ppm on the SR.N4 has achieved engine overhaul lives in excess of 4000 h except for the power turbine, for which the life is 2000 h. These values, although not ideal, have been shown to be commercially acceptable. The system developed to achieve this level[6] consists of four stages (Fig. 21). By drawing air from the craft plenum chamber, the lift fans are used as first-stage separators. Air is drawn from the dryer part of the plenum through reverse flow louvers, where a further quantity of water is thrown off. The remaining water is in the form of a relatively fine mist, and, by passing this through a coalescer formed of loosely knitted polypropalene fiber, much of the remaining water is removed. The velocity of the air through the coalescer must be kept below a critical value, which requires a relatively large cross-sectional area. The fourth stage consists of a mat of nylon felt that removes those particles (aerosols) that are too fine to coalesce in stage 3. Typically, the power loss across the filters is of the order of 7% of the engine cruise power, and when the loss of lift air is taken into account, this figure rises to 11%.

There is, therefore, a need to return to a system where the engine air is taken directly from the atmosphere. A system used successfully on gas-turbine-driven ships involves two stages of hooked vanes, which separate the water by inertia, with a coalescing stage between (Fig. 22). Power loss through this type of filter would be of the order of 8%. Plans are in hand to fit a new design trial installation of similar concept on the BH.7 Mk.2.

E. Craft Motion and Cushion Dynamics

In addition to general motion prediction and dynamic model tests in towing tanks and free flight, specific response research has been conducted using facilities at the former Hovercraft Unit of the National Physical Laboratories (N.P.L.), Teddington and at the Cranfield Institute of Technology. At N.P.L., an oscillating table facility was developed which permitted investigation of model motion with forcing in heave and/or pitch. The three major British hovercraft manufacturers conducted a joint research program using this facility to determine to what extent the response was linear and to determine factors contributing to the response. This latter aim proved difficult to achieve, but it was established that hovercraft response is substantially linear over a moderate range of conditions. This is illustrated in Figs. 23 and 24, which compare the heave and pitch response of a model fitted with a B.H.C. bag/finger type of skirt including lateral cushion dividers, with simple linear spring/damper response curves. It may be noted that a similar result was achieved for the same model without lateral cushion dividers, the main difference being that the pitch natural frequency reduced from 1.7 down to 1.1 Hz.

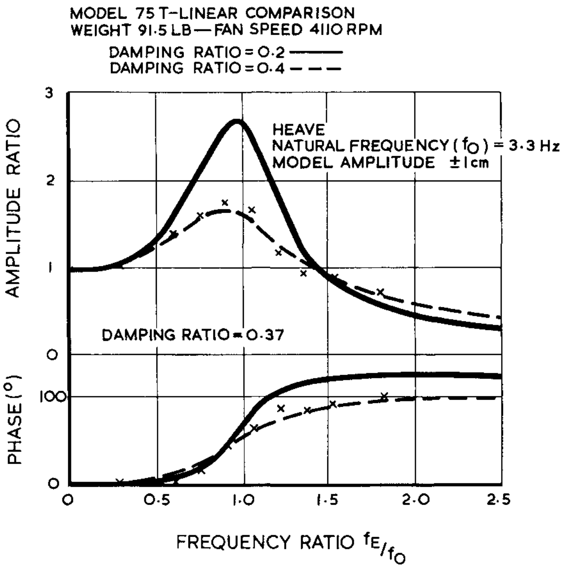

Fig. 23 Comparison of model results with spring/damper theory: heave.

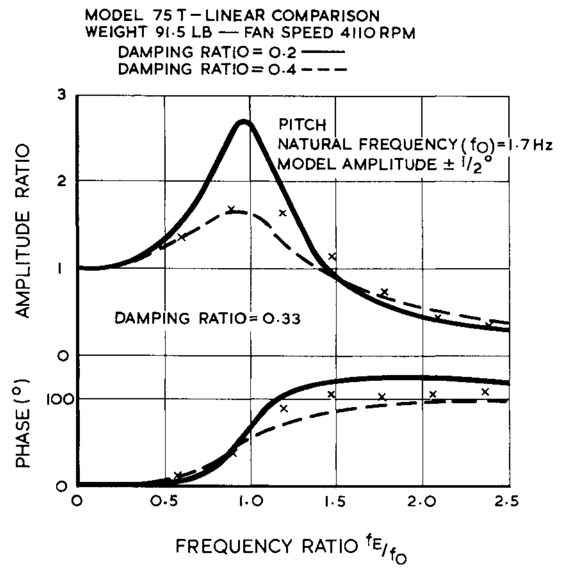

Fig. 24 Comparison of model results with spring/damper theory: pitch.

Cranfield has a continuing program using a whirling arm such that the hovercraft model runs around a vertical wall on which various waveforms are superimposed. Testing in such an acceleration field is intended to give representative loadings and response in flexible structures which are not scaled in the normal 1-*g* field (see, e.g., Ref. 7).

For craft under development, there is always a program investigating response with scale models, either freeflight or using towing-tank facilities at B.H.C. or N.P.L. Feltham. As part of the general safety and integrity aspect, model testing and analysis into the beam-on capsize situation has been made on dynamic models of current designs (see, e.g., Ref. 8), and further work is proposed. Current new sidewall craft model testing has been extended to meet the requirements of simulating severe damage and monitoring sinkage and attitude response in limiting sea conditons.

Measurements have been made at N.P.L. of the pressure/flow characteristic of a 12-in.-diam model HEBA B fan, under dynamic conditions, i.e., with a time-varying throttle causing fluctuation of the working point (see Fig. 25). The pressure vs flow graphs of Fig. 26 show fluctuation of flow about two steady flow values, achieved by opening an additional bleed to atmosphere, downstream of the fan. These loops are shown superimposed on the "static" characteristic obtained by drawing a mean line through the 0.5-Hz loops. The pressures, flows, and frequencies are model scale. At SR.N6 size, the corresponding frequencies would be 0.19, 0.76, and 1.89 Hz, the two lower ones being typical of encountered wave frequencies for this craft. Clearly, accurate computational models of craft motion should incorporate the dynamic rather than the static fan characteristics.

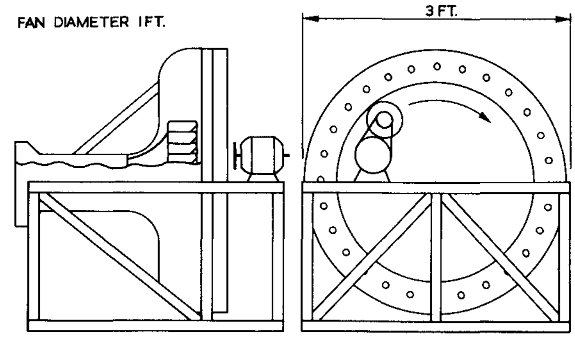

Fig. 25 National Physical Laboratory (N.P.L.) fan forcing rig.

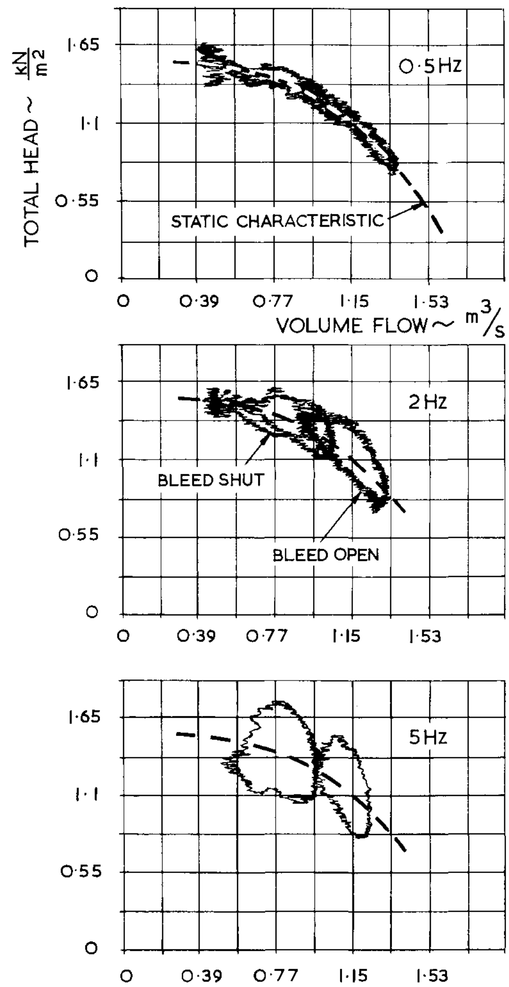

Fig. 26 Dynamic behavior from N.P.L. tests.

Motion and control measurements have been obtained during full-scale trials on all current B.H.C. and V.T.L. craft. Craft motions and skirt loads were obtained on a Hoverlloyd SR.N4 during commercial operation throughout March 1975, in support of Bell Aerospace Company work on the Surface Effect Ship Programme. Various finger materials also have been evaluated on SR.N4 craft for this program.

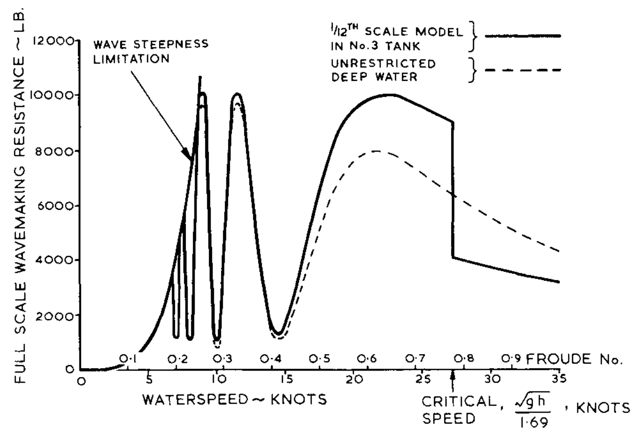

Fig. 27 SR.N4 theoretical low-speed wavemaking resistance characteristics.

In the sidewall case, improvements in ride have been achieved by Hovermarine by employing passive systems with suitable fan characteristics. Active systems are being considered, and these shortly will be the subject of testing with models and HM.2.

F. Other Aspects

Other areas of research within the industry have included government-funded studies to investigate the application of the hovercraft to mine countermeasures (MCM) operations. Security restrictions preclude any discussion of the results obtained, but the basic concept of an MCM hovercraft has been shown to be feasible, and the problems of control and track-keeping have been examined in some depth. These studies were carried out under joint contracts placed with B.H.C. and V.T.L. As part of this work, model measurements of the low-speed drag characteristics of the BH.7, SR.N4, and VT.2 were made which have extended our knowledge of the hitherto relatively unexplored speed regime below the primary humps, where the basic wavemaking forces vary considerably (see, e.g., Fig. 27).

The Naval Hovercraft Trials Unit, N.H.T.U. (formerly I.H.T.U. and I.H.U.), in conjunction with Admiralty Experiment Works (A.E.W.), has been evaluating hovercraft for military purposes, having at one time or another appraised most of the craft types produced. During the past few years, N.H.T.U./A.E.W. have carried out trials with various craft, simulating the towing of MCM equipment and investigating a number of other associated aspects such as control and track-keeping characteristics, noise levels, and underwater signatures. Recently, these trials have included the special hire of VT.2, SR.N6 Mk.6, and SR.N4, the latter in association with Hoverlloyd Ltd., who provided operational crews. The feedback from these trials has provided the industry with useful background data for MCM studies.

The National Research Development Corporation, and its subsidiary Hovercraft Development Ltd. (H.D.L.), has continued to promote hovercraft generally. H.D.L. have been involved in organizing a draft specification for a future cross-channel hovercraft and promoting the interests of the manufacturers among users and United Kingdom government departments. H.D.L.'s own research and development efforts have been directed mainly toward cushion development. This includes the concept of deep cushions coupled with an efficient pitch and roll control system and the further development of simple low drag skirts. A man-carrying craft, HD.4, currently is being used to evaluate a center-of-pressure shift system for this purpose.

Research work by the Cranfield Institute of Technology already has been mentioned, but other educational establishments such as the Portsmouth Polytechnic and Sheffield University should be mentioned for their work on semisubmerged A.C.V.'s and studies of the airflow around the edges of hovercraft skirts, respectively.[9,10] A further aspect of skirt research has concerned the material from which it is made and the methods used to make joints and attachments. The material invariably takes the form of a woven core fabric coated on both sides with rubber or plastic, and efforts continually are being made to develop new types of material. F.P.T. Industries Ltd., Avon Industrial Polymers, and Northern Rubber Ltd. have been closely associated with research in this field, whereas V.T.L. and B.H.C. (with the cooperation of the craft operators) have been involved with the evaluation of the materials. Half of the segments currently fitted to the VT.2, for example, are manufactured from new materials undergoing evaluation. Various methods have been developed to make joints and attachments on the skirts, and experience has shown that hot and cold bonding, bolting, riveting, and stapling all can be employed effectively in various areas of the skirt structure, depending on the types of loads sustained. This research and development contains a great deal of proprietary information, which is the subject of patent action and cannot be discussed in detail at the present stage.

Fig. 28 SR.N6 Mk.2 with Air Vehicles ducted propeller.

III. Craft Developments

A. British Hovercraft Corporation Ltd.

1. SR.N6

This craft type has been in continual development since it was derived from SR.N5 in 1965. Over the past 10 years, 43 craft have been built incorporating numerous build standards. For the present paper, it is proposed to comment on three recent development aspects: noise reduction, improved seakeeping, and controllability:

1) Noise reduction. Awareness of the hovercraft noise problem arising, particularly on SR.N6's, from the use of high-tip-speed air propellers has existed for many years. The problem has been felt particularly strongly by operators of hovercraft engaged in ferry operations on routes close to built-up areas. The two systems investigated have been the following:

a) Shrouded propeller. The design and building of the duct was subcontracted by Hovertravel Ltd. to Air Vehicles Ltd. and Robert Trillo Ltd. The main aim was to reduce the tip speed of a standard SR.N6 propeller by "cropping" or reducing its diameter, from 9 ft to 6 ft 10 in., and restoring the thrust by fitting a duct around the propeller. In order to minimize the likelihood of the propeller rubbing the duct in service, the duct had to be rigid and mounted in a manner to avoid vibration. In addition, the whole installation had to be as light as possible to avoid significant reduction in craft payload. The cylindrical drum structure of the duct was designed in light alloy, and a bell-mouth entry and downstream diffuser section were made in fiberglass, using heavy, accurate molds. The inner section of the structural box was covered in polyurethane foam, to avoid undue damage should the propeller contact the duct. The whole structure gave a weight penalty of 300 lb. The duct installation was fitted to a military SR.N6 Mk.2 (see Fig. 28), and successful, albeit limited, trials have been conducted by N.H.T.U., Hovertravel Ltd., and B.H.C.

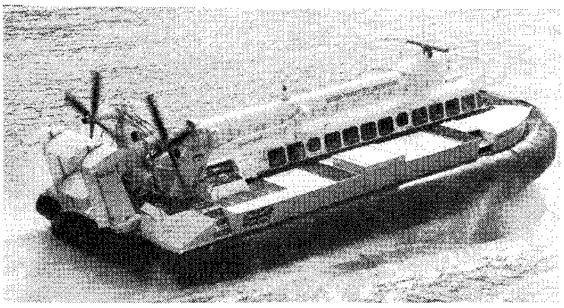

Fig. 29 SR.N6 Mk.6.

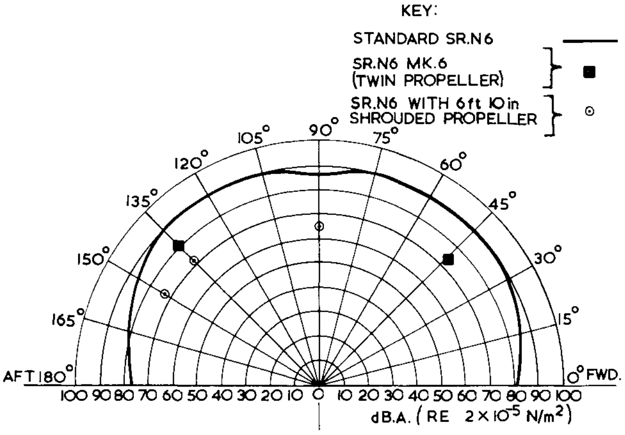

Fig. 30 SR.N6 external noise; "A"-weighted levels at 500 ft, cruising conditions.

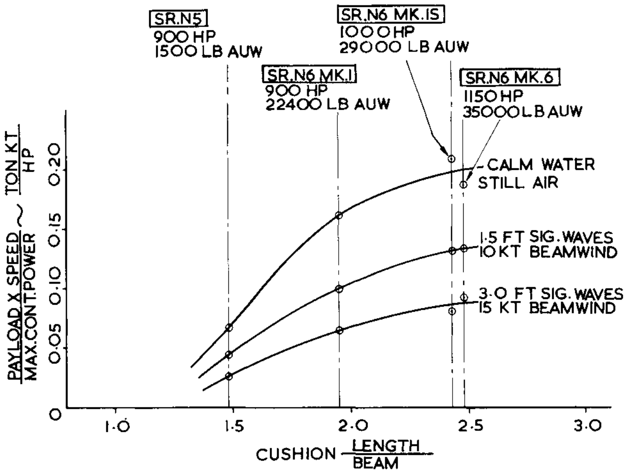

Fig. 31 SR.N5/N6 craft development.

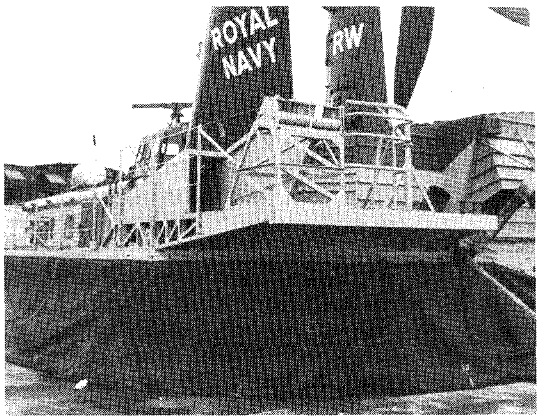

Fig. 32 BH.7 Mk.2 fitted with MCM gear.

b) Twin low-speed propellers, SR.N6 Mk.6. This craft, which is similar in length to the SR.N6 Mk.1S, is fitted with twin Dowty Rotol, 10-ft-diam propellers coupled via two fixed pylons with gearboxes and a new splitter gearbox (see Fig. 29). Compared with the standard single 9-ft-diam system, this has resulted in a propeller tip speed reduction from 808 to 420 fps (i.e., tip Mach number reduced from 0.73 to 0.38) at typical operating speeds.

An analysis of B.H.C. and H.S.D. external noise level measurements indicates that, at similar thrust conditions, the two systems give a similar noise reduction compared with the standard craft, this reduction being of order 13–15 dBA. A comparison of "A"-weighted levels, estimated at a 500-ft radius, for typical cruise conditions is shown in Fig. 30. Although the shrouded propeller noise reduction is seen to be relatively greater in Fig. 30, it should be noted that the twin propeller system has much-enhanced handling qualities, so that in service the SR.N6 Mk.6 is expected to prove the quieter.

2) Improved seakeeping. The trends of increasing length-to-beam ratio for the SR.N5/SR.N6 series have resulted in considerable improvements in ride comfort. In addition, the SR.N6 Mk.6 has incorporated a new skirt form, which is tapered from 5¼ ft deep at the bow to 4 ft deep at the stern. Compared with the performance with the standard parallel 4-ft-deep skirt, this has led to a further motion improvement. In terms of overwave performance, the new skirt responds better, and a waterspeed increase of over 5 knots has been measured in the larger seas, around 3 ft significant height, with an operational limitation increase from force 7 to force 8. The trend of transport efficiency improvement in terms of payload times cruise speed divided by cruise power is illustrated for the SR.N5/SR.N6 series in Fig. 31.

3) Controllability. The use of the differential pitch control facility of the twin-propeller SR.N6 Mk.6 has provided greatly increased maneuvering capability and has shown that the aft yaw control ports fitted to the standard craft are unnecessary.

2. BH.7 Variants

The BH.7 is primarily a military craft, the design of which is adaptable to a variety of roles, logistic, coastal patrol, fast attack, and mine countermeasures (MCM) work. The prototype BH.7, the Mk.2 (see Fig. 32), which is operated by N.H.T.U., has been modified extensively, the main alterations being 1) the replacement of the 19-ft-diam propeller with a 21-ft-diam fiberglass type, 2) the fitment of a "clamshell" type of bow door and ramp, and 3) the fitment of mine countermeasures winches and towing gear (see Fig. 32). The latter modification was incorporated as a result of the encouraging results of earlier MCM towing trials undertaken on this craft.

Parallel with the development of the Mk.2 has been the interest of the Imperial Iranian Navy, who ordered their first two BH.7 craft shortly after the building of the Mk.2. These were of Mk.4 type, i.e., similar to the original Mk.2 but with a bow-loading door and ramp fitted. Subsequently they have taken delivery of four more Mk.5A craft designed to carry missile launchers on open-side decks and also fitted with 21-ft-diam propellers (see Fig.3).

3. SR.N4

This section briefly reviews the improvements carried out on the Mountbatten class SR.N4 amphibious hovercraft currently operating on the English Channel "short" sea routes and indicates the improvements anticipated from a simple but substantial lengthening of the craft. A contract now has been signed with British Rail to lengthen both of their craft, and design and manufacture are now in progress. The first craft returns to B.H.C. early in 1977 and will be back in service in its modified form in the spring of 1978.

1) Current operational craft. English Channel operations with SR.N4 began in the summer of 1968 with the in-

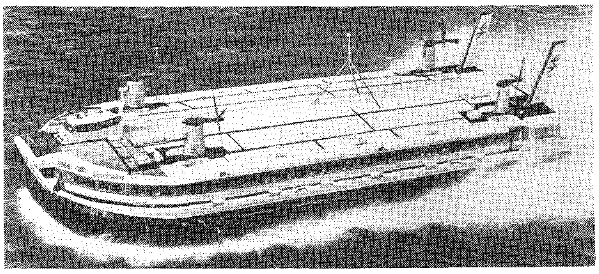

Fig. 33 SR.N4 Mk.3.

troduction of the Princess Margaret on the British Rail Hovercraft Seaspeed routes from Dover to Boulogne/Calais. Two more craft (Swift and Sure) commenced operations in the spring of 1969 on the Hoverlloyd route from Ramsgate (Pegwell Bay) to Calais. These since have been supplemented by one further Seaspeed craft (Princess Anne) in 1969 and one further Hoverlloyd craft (Sir Christopher) in 1972. The craft have been under continuous development throughout their operational period. In particular, the skirts have been developed extensively, initially as described in Ref. 11, and subsequently by the introduction of the "tapered" skirt, which increases the bow structural clearance by about 2 ft and gives improved rough sea capability. Skirt integrity has been improved by research and development into detail design, materials, and skirt-manufacturing techniques. The two Seaspeed craft are of the Mk.1 type with a payload capacity of 32 cars and 254 passengers. The three Hoverlloyd craft have been converted to a Mk.2 standard in which the cabin width has been increased to give some 15% greater payload capacity on the same cushion area so that it now carries up to 37 cars and 280 passengers.

2) Lengthened SR.N4-SR.N4 Mk.3. Both channel operators are actively expanding their present services. Hoverlloyd have placed an order with B.H.C. for their fourth SR.N4 Mk.2, which is currently under construction at Cowes for delivery in June 1977. The approach adopted by British Rail is to lengthen their two existing craft to give a considerable payload increase. The technical objectives of lengthening are to 1) substantially increase payload without reduction in performance and without changing engines, 2) increase seakeeping ability and passenger comfort, and 3) increase craft hump speed and thus performance in extreme weather conditions. Application of these objectives to the SR.N4 showed that total operating costs, including financing, could be reduced by 25% on a cost per passenger mile basis if the craft were lengthened by 55 ft. This cost reduction assumes new craft in both cases using 1974 prices. In addition to lengthening the craft by 55 ft, the passenger cabins will be widened as already carried out on the Hoverlloyd Mk.2 craft. Car-carrying capacity will be icnreased from 32 to 59 cars and passenger capacity from 254 to 400 with increased exits for a quick turnaround at terminals. The achievement of satisfactory performance with this large payload increase is associated partly with the provision of additional thrust by increasing the cruise output power level of each of the Proteus engines from 3400 to 3800 hp and increasing the diameter of the H.S.D. propellers from 19 to 21 ft, but it is also due to a craft efficiency increase associated with the geometry change as discussed later. The appearance of the projected craft is illustrated by the photographic simulation given in Fig. 33, which also lists the leading particulars.

3) Technical aspects of lengthening. In the contract to lengthen the two SR.N4 Mk.1 craft for British Rail Hovercraft, the lengthening is achieved by physically cutting the parallel section. The craft is built of structural modules just under 8 ft in length, and the lengthening was considered in multiples of these lengths, which we have termed "bays." A comprehensive investigation to decide the degree of lengthening took account of the following factors: 1) customer requirements, including such factors as a requirement for the same performance as the Mk.1 craft but in 2-ft higher seas and maintenance of turnaround times at hoverports as far as possible; 2) capital cost and running costs; 3) structural problems: as length increases and maximum laden weight increases with it, the degree of modification of the existing components becomes increasingly more difficult and comprehensive, increasing conversion costs nonlinearly; 4) performance: although in general performance must decrease with increasing laden weight, this is offset by some of the advantages of lengthening as discussed in subsequent paragraphs; and 5) controllability, particularly in high winds in the vicinity of hoverports. As a result of these deliberations, and after many discussions with the customer, it was decided to lengthen the craft by 7 bays, or 55 ft, a percentage increase in length of 43%. The concept of lengthening the craft, although retaining the original lift fan system and lift power, depends upon certain advantages gained from the increased length/beam ratio and the maintenance of the original cushion pressure. In terms of hydrodynamic wavemaking resistance, its peak value at primary hump occurs at increasing speed with increasing cushion length (changing from 21 to 27.5 knots as length is increased by 55 ft). The maintenance of constant cusion pressure and the change of length/beam ratio insures that the resistance level is not changed significantly. Performance in head seas tends toward the region of hump speed as wind and sea conditions worsen, giving a 55-ft lengthened craft a basic speed advantage of order 6–7 knots. In large head seas, the relative importance of wavemaking resistance reduces, and the speed advantage has been maintained by skirt refinement and the increased thrust available from the increased propeller size and an increase in maximum continuous power from 3400 up to 3800 hp/engine. Initial comparative data obtained from a model lengthened by 6 bays is presented in Fig. 34 in terms

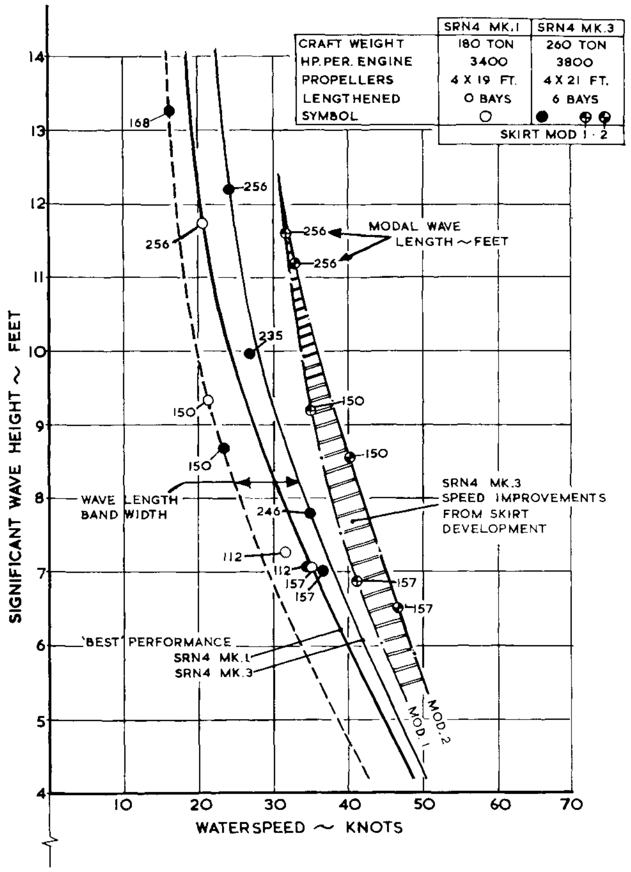

Fig. 34 SR.N4 MK.1 and Mk.3 relative performance on beam wind headings.

	SR.N4 Mk.1	SR.N4 Mk.3
CRAFT WEIGHT	180 TON	260 TON
H.P. PER ENGINE	3400	3800
PROPELLERS	4 x 19 FT	4 x 21 FT
LENGTHENED	0 BAYS	-6 BAYS

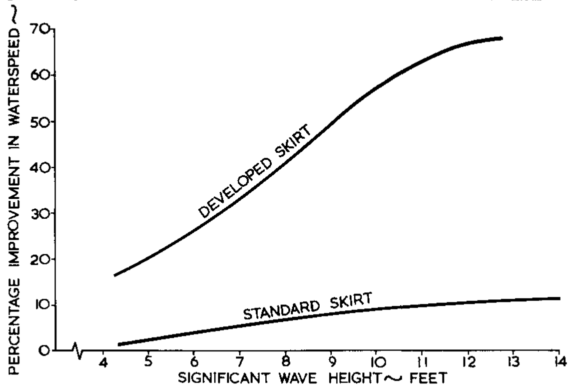

Fig. 35 SR.N4 Mk.3 percentage performance improvement relative to SR.N4 Mk.1 on beam wind headings.

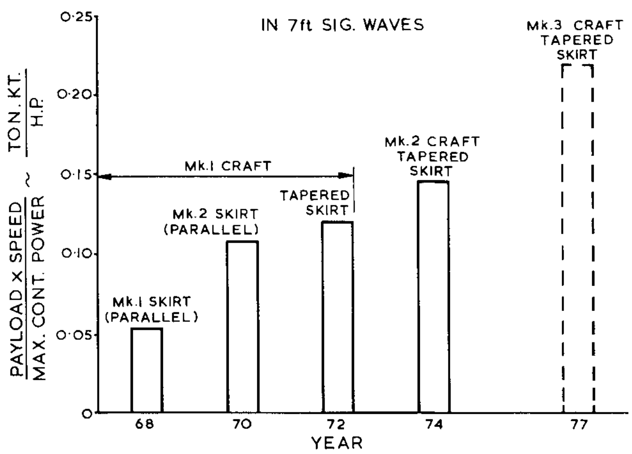

Fig. 36 SR.N4 efficiency improvement in rough water with skirt design.

of achieved waterspeed for various wave heights. This shows results for a number of wavelengths. Some further performance improvements achieved with skirt design refinements also are illustrated. These refinements have involved variations of skirt inflation pressure and detail changes of the bow fingers (Mod. 1) and a more responsive rear skirt system (Mod. 2). Figure 35 indicates the percentage performance improvement achieved in this development and demonstrates the relative effects of lengthening and the skirt modifications. Similar refinements, and others involving more radical skirt design variation, currently are under investigation on a model lengthened by the full 7 bays. The gains in transport efficiency in high sea states since the SR.N4 first entered commercial service in 1968 are shown in Fig. 36. The efficiency in 7-ft significant seas will be some 40% greater than the current craft. Significant reductions in pitch response, which may be anticipated for the lengthened craft, are detailed in Fig. 37. Initial model tank test results are overlaid on a basic pitch magnification factor diagram derived from available B.H.C. craft motion data. The eight pairs of cases overlaid are each for the same wave height, wavelength, and forward speed for the two craft, at fixed longitudinal c.g. It will be noted that the reductions are mainly due to change in wavelength relative to craft length. The model data at optimum (minimum resistance) longitudinal c.g. for each craft are presented in Fig. 38 in relation to pitch response and in Fig. 39 in relation to bow vertical acceleration.

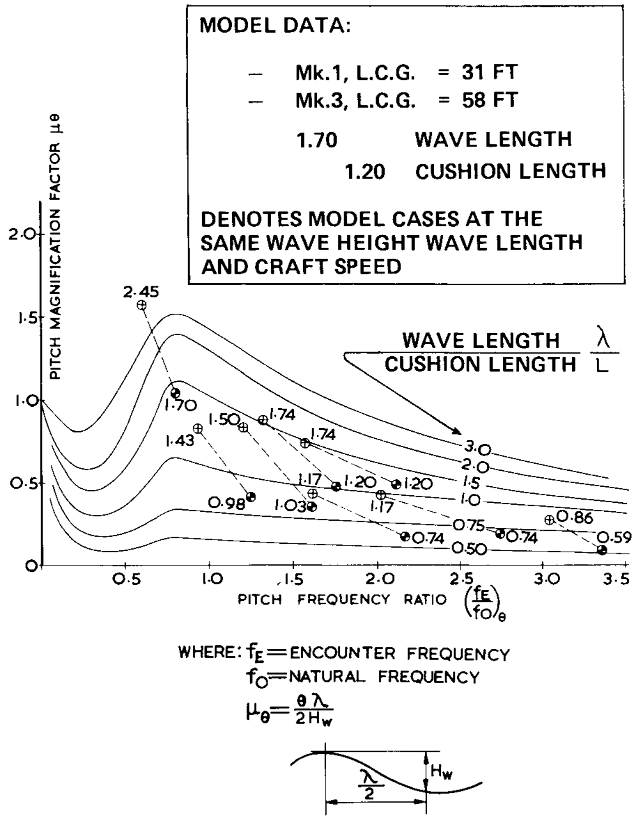

Fig. 37 Relative SR.N4 Mk.1 and Mk.3 pitch response; model data and basic response diagram.

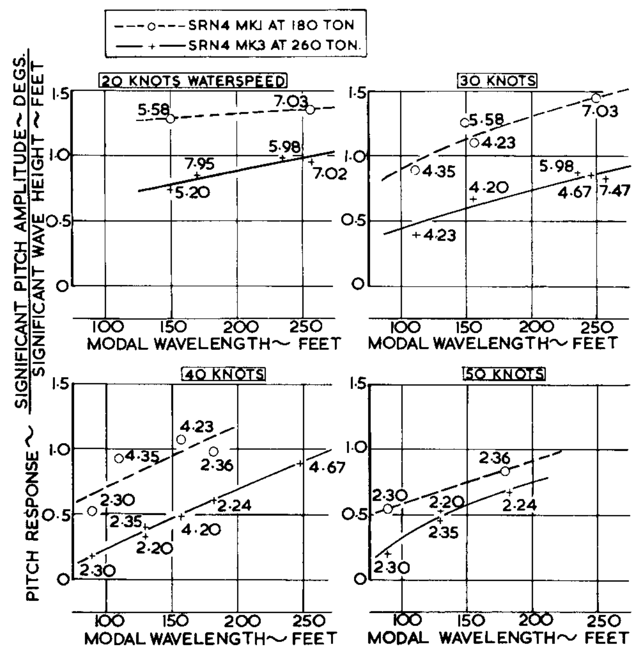

Fig. 38 SR.N4 Mk.1 and Mk.3; comparative pitch responses at minimum-resistance longitudinal c.g.'s.

B. Vosper Thornycroft Limited

1. VT.1

VT.1 was designed in 1968 as a passenger/car hoverferry for operation in reasonably sheltered waters at speeds of about 30–40 knots. It introduced several new features on a fairly large hovercraft, about 100 ft in length and 90 tons displacement.

The cushion systems, including air feed and stability devices, were new and were developed using two-dimensional

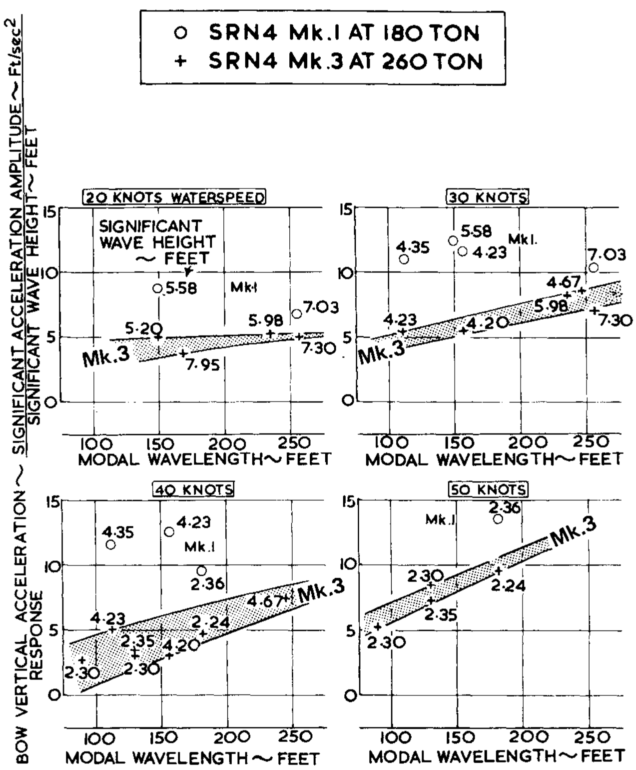

Fig. 39 SR.N4 Mk.1 and Mk.3; comparative bow vertical acceleration responses at minimum-resistance longitudinal c.g.'s.

test rigs and a towing tank model. The single-cell skirt followed closely that developed by Hovercraft Development Ltd. and initially incorporated a skirt shift mechanism that functioned in both pitch and roll modes. Although this was very effective in enabling craft pitch and roll trim to be changed rapidly, it did give rise to problems of mechanical reliability of its operating mechanism and subsequently was removed when operating experience showed that craft stability in pitch and roll was satisfactory without it. The choice of waterscrew propulsion instead of airscrews stemmed from the requirement for low external noise, felt necessary for a commercial ferry, and minimum total installed power.

The operation of VT.1 002 and 003 between Malmo and Copenhagen in 1972 showed the design to be technically sound but did show up areas where detail modifications could be made to improve reliability. Development of the skirt system was directed primarily at increasing skirt life, by the introduction of new improved skirt materials and the incorporation of detail design changes where problems arose from obvious design inadequacies.

2. VT.2

The VT.2 (Fig. 4) is the first amphibious hovercraft to be built by Vosper Thornycroft and is intended for military applications. The craft is powered by two Rolls-Royce Proteus gas turbines. Each engine is located in an engine room, port and starboard, outboard of the center bay, and between the forward and aft accommodation areas. Each drives one variable-pitch propulsion fan and one bank of four lift fans through a system of gearing and shafting (Fig. 40).

The propulsion fans are mounted in ducts located side by side at the aft end of the craft, just above the roof level. Spaces for the lift fans are located within the craft superstructure together with the engine rooms, generator, and electrical distribution compartments. Space for weapon systems or logistical loads and accommodation facilities occupy the remaining 70% of the whole craft area. The structure is constructed robustly in aluminium alloys suitable for a marine environment.

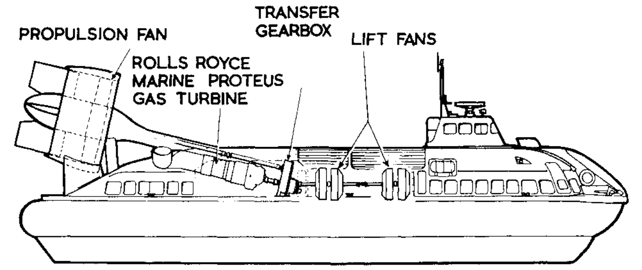

Fig. 40 VT.2 machinery and transmission.

A machinery and power transmission arrangement, which is novel for hovercraft but is derived directly from patrol boats, has been adopted for the VT.2 design: this features the mounting of the propulsors, engines, and the main gearboxes at an angle of approximately 13½ deg to the horizontal (Fig. 20). The reason for this innovation, which at first glance gives the craft an unusual but distinctive appearance, is the simplification of the transmission and gearbox design. There is only one gearbox in each power train; the lubrication, cooling, and associated systems are simplified correspondingly, and maintenance tasks are reduced.

It follows from the machinery layout that the main engines and the gearboxes are located close to the longitudinal center of gravity position, and this is best for reasons of craft trim; also, the overall height of the craft is lower than would be the case if the ducted fans were to be mounted above the roof line, the lower profile reduces the chance of detection, and the lower height of the center of gravity aids craft stability.

Compared with a propulsor mounted horizontally, the inclination of the VT.2 propulsor results directly in a 2.5% loss in thrust; this is considered to be entirely acceptable in view of the favorable aspects mentioned previously. Each engine output shaft drives through a flexible gear coupling into a main gearbox, which has two output shafts; one drives the propulsion fan via the main propulsion shaft; the other drives the four lift fans.

A flow of ventilation air for the engine rooms, which contain the gearboxes and several auxiliaries, and the combustion air for the main engines is supplied under pressure from the skirt-distribution loop. Before the combustion air reaches the engines, it passes through a demisting system consisting of one stage of knitted mesh filters and a second stage of nylon felt filter panels. This choice of air-cleaning system permits the craft to operate over sandy beaches without the choking of filters to which other demisting systems appear to be prone. The ducted fan propulsion system is a significant advance in hovercraft technology, in terms of compactness and noise reduction (as already discussed).

Two variable-pitch propulsion fans are fitted to VT.2, and at 13.5 ft diam they are the largest ducted air propulsors in the world. Manufactured for the VT.2 by Dowty Rotol Ltd., the seven-blade all-plastic fans are not handed and are controlled by a variable-pitch mechanism, designed to give a normal maximum rate of blade travel of 15 deg/s over a range of 85 deg, which is split roughly equally between ahead and astern.

Each fan is mounted within an aluminium alloy duct, which also supports the airflow straighteners and the rudders (Fig. 20). The two ducts are of Vosper Thornycroft Ltd. design and manufacture. To match the fan design, the i.d. is a little more than 13.5 ft, and the duct length in a streamwise direction is 8.75 ft.

To minimize the rotor tip running clearance and so maintain a high blade efficiency, it is necessary for the duct to have little deflection under side loads or due to vibration. At a low forward speed, the duct itself generates almost 50% of the total thrust, and at the highest point it deflects 2.5 cm (1 in.) forward under these conditions. This effect is relatively easy to accept in the design, as the only close-running components affected are the fairing structures at the hub, where the deflection is correspondingly less.

Close limits on lateral movement of the duct and the desire for low weight make the design of both duct and the support structure a major structural problem. The VT.2 duct follows aircraft wing design practice, using a fully stressed-skin construction and four ring spars, making up a forward box and rear box. The forward main ring spar is at the 15% chord position and carries the molded glass-reinforced plastic (GRP) duct leading edge; the rear ring spar is at 70% chord and serves as the break joint for removal of the aft portion, which can be detached by uncoupling eight pairs of bolts.

The inside surface of the duct is cylindrical and flush-riveted. The achieved manufacturing tolerance on diameter is ± 2.5 mm (±0.1 in.), which is equivalent to 0.12% on the diameter. Due to centrifugal loading at the running speed, the fan diameter increases by 3.5 mm (0.14 in.) and naturally has its own manufacturing tolerance. In the plane of the rotor, the duct inner skin is recessed 12.7 mm (0.5 in.) to take an expanded foam insert, which permits the aerodynamic clearance to be reduced and yet avoids structural or blade damage in the event of excessive duct movement arising from high wind or control surface loads or rapid lateral deceleration.

The VT.2 visited the Greenwich Naval Equipment Exhibition in September 1975 after the first six sorties at sea and by the end of May 1976 had completed over 200 h at sea. A number of points have come out of the trials, the first and foremost being the good reliability of the craft and its systems. The Proteus engine, which is now well proven in the marine environment, has operated very well to date with no significant problems, and the fact that it is installed nose down in the craft has had no detrimental effect on its performance or reliability. The simple mechanical controls have proved effective, and, although they are heavier to operate, this is outweighed by their good reliability. It was found that the propulsion fan blades could move faster than the intended 15 deg/s, and the rapid unloading of power could cause the engine to shut down. This was corrected by flow control of the exhausting hydraulic fluid at the fan hub.

Strain measurements on the ducted propulsors taken from gages embedded in the GRP skin of the blades show that the load levels are well within the allowable values over almost all of the envelope of blade angle and rotational speed, including astern pitch, with a small band of speed below the cruise condition where prolonged running should be avoided. The ducts themselves have presented no major structural problems, particularly regarding initial concern of duct and fan-bearing stiffness. However, two minor problems have been encountered. The first was the separation of the plastic foam linings, which are fitted round the inside of the duct to maintain a close-tolerance rotor tip clearance, and this has been corrected by changing the adhesive originally used. The second problem was the loss of thrust in reverse pitch, i.e., below expectation, due to the comparatively sharp trailing edge of the duct. This was regained by providing an increased trailing edge radius to improve the airflow, which was expected to degrade ahead thrust. In the event, the ahead thrust was not affected detrimentally, and the thrust in reverse pitch was increased markedly.

As is usual with manual servotab and geared tab controls, some development was required to bring the rudder control to the present standard. Also, vortex generators were added to the rudders and the aft portion of the center body fairing to cure the problem of flow separation over the rudders and to improve the rudder power.

The skirt and cushion system have behaved well. There was an early indication that the craft could develop a high deceleration plough-in, which was accentuated by engine shutdown due to power shedding, as mentioned earlier. This situation was investigated by further model trials, which resulted in a change in the bow skirt geometry. An interesting operating feature of the craft is the way in which it adopts an inward bank or heel of 1-2 deg when in a turn maneuver; this effect was apparent in the early model tests but the significance not understood until attention was drawn to it by the craft captain.

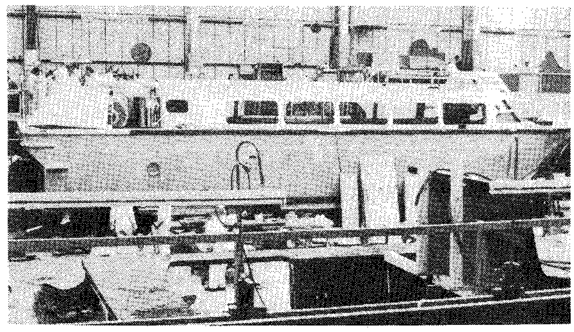

Fig. 41 Hovermarine HM.2 Mk.IV under construction.

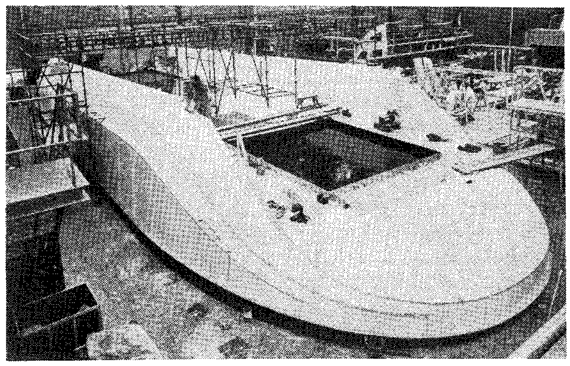

Fig. 42 Hovermarine HM.5; tooling under construction.

C. Hovermarine Transport Ltd.

The Hovermarine HM2 Mk.1 was launched in early 1968 and immediately after basin trials demonstrated the performance potential of the craft. With 800 hp, it was capable of carrying 5 tons of payload at approximately 35 knots. This 50-ft craft has been modified over the years to increase its reliability and passenger comfort, and now, including those craft on order, 40 craft have been sold to 16 different countries. The Mk.II and Mk.III versions of the craft have benefited from improved transmission, lower internal noise, better seakeeping due to improvements in skirt design, and, whereas the Mk.I version literally could be described as a "marine bus," the internal design of the Mk.III is more akin to aircraft standards complete with full air conditioning.

The next big step forward was to take a further look at the economics, and a considerable improvement now has been derived by the addition of 10 ft to the overall craft length. This, with further machinery alterations to allow for 10% more power, has resulted in an increase of payload of 45% with costs not exceeding 20% over those of the Mk.III version. This craft, the Mk.IV, is shown under construction in Fig. 41. The overall length-to-beam ratio has been increased from 2.55 for Mk.III to 3.05 for Mk.IV. The transport efficiency has increased from 0.2 to 0.27 payload ton knot/cruise hp in calm conditions and from 0.15 to 0.19 in typical rough water.

D. The Next Five Years

The next five years will see a continuation of research and development effort, which will lead to the introduction of new hovercraft designs. Development of present designs will continue with special customer requirements and probably will include such major developments as the lengthening of BH.7 and VT.2, possibly with increased power.

The first entirely new craft to appear will be the Hovermarine HM.5 sidewall craft illustrated in Figs. 42 and 43, due to be launched in 1977. Both civil and military versions are

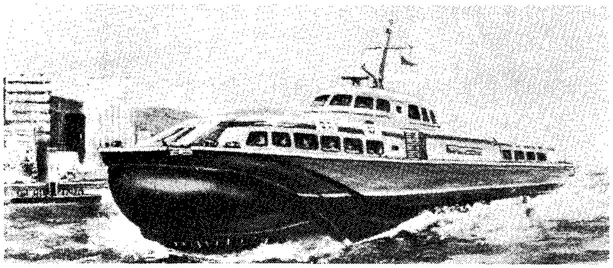

Fig. 43 Hovermarine HM.5; artist's impression.

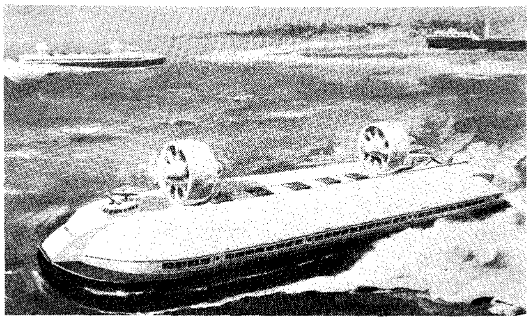

Fig. 44 BH.88; artist's impression.

envisaged when initial development has been completed. The craft is 75% longer than HM.2 Mk.III and will carry 177 passengers with considerably increased comfort compared to the 65 passengers carried by HM.2. Length-to-beam ratio will be 2.66 and the transport efficiency in the 0.2 to 0.22 payload ton knot/cruise hp range.

The Royal Navy, which recently has declared its interest in hovercraft for the mine countermeasures role,[12] will continue operational evaluation at N.H.T.U. and will study craft characteristics and detailed roles. It is to be hoped that these assessments will crystallize into the choice of a craft and the placing of a contract for craft manufacture. Whether such a craft would be of new design, or an adaptation of an existing design, and whether it can survive future defense cuts can only be pure speculation at the present stage.

Toward the end of the period, designs for the replacement of civil SR.N6 and SR.N4 craft will have to commence. These craft will incorporate the results of market research and engine developments, in addition to the increased efficiency described earlier in this lecture. An impression of a possible B.H.C. version of a new cross-channel craft (Fig. 44) was given in Ref. 1. Preliminary designs such as these can only be taken as an indication of current thinking and are subject to continual revision and reassessment. Progress to date is sufficient to indicate that the new craft will offer a significant advance in operating economics, seakeeping, passenger comfort, and reliability.

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