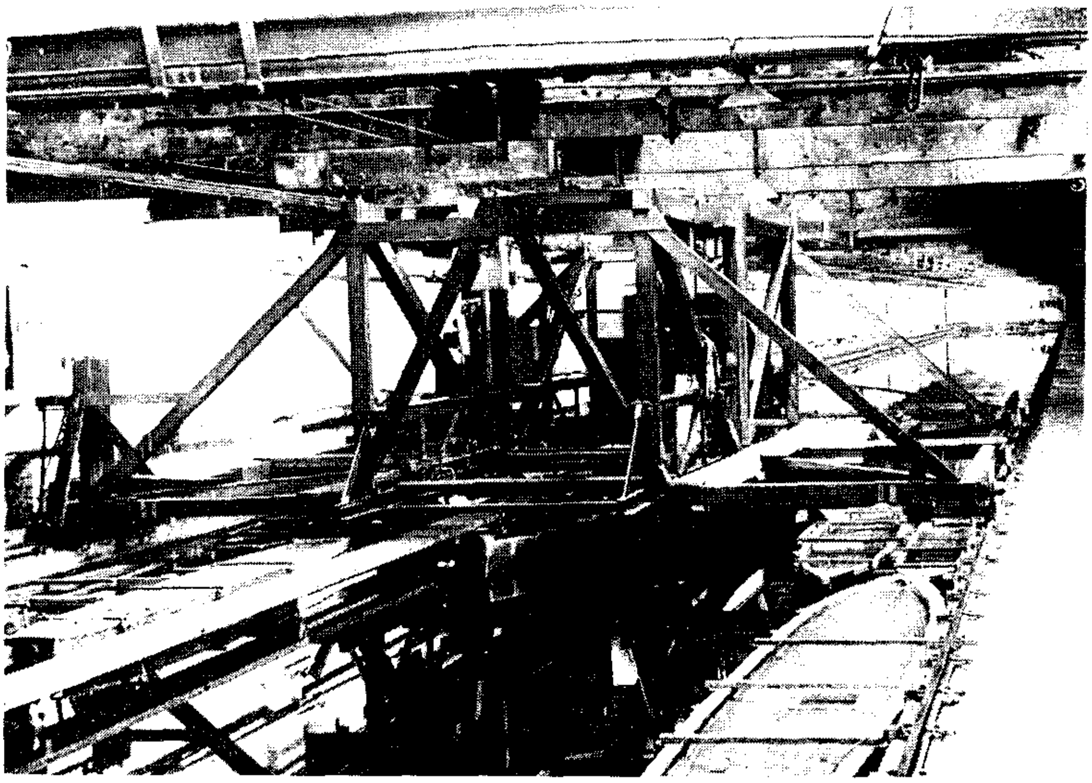

FIG. 1—No. 1 SHIP TANK
400 FEET × 20 FEET : MAX. DEPTH 9 FEET

THE ADMIRALTY EXPERIMENT WORKS, HASLAR

BY

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Introduction

This paper is presented as a tribute to William Froude on the occasion of the unveiling of the memorial plaque to his genius, which marks the site of the original experiment tank known as the Admiralty Experiment Works, Torquay. This pioneer enterprise in ship model research formed an early prototype for comparable facilities and methods now found the world over in most countries with maritime interests. The present paper deals with developments at the Admiralty Experiment Works, Haslar, to meet the requirements of the modern Navy. Ship model research has continued at Haslar for nearly seventy years and it will be appreciated that any review must accordingly be of a general character and many details are inevitably omitted.

Originally the investigations were largely concerned with improvements in hull and propeller design to ensure the highest possible standards of propulsion. This work is now more comprehensive following the increase of size, speed, and number of classes of H.M. ships. In addition, the scope of the investigations has expanded appreciably and propulsion is now only one of a number of objectives. Investigations are called for in parallel to secure the requisite high operational standards in ship motion and seaworthiness, steering, freedom from vibration, and other qualities. The functions are broad and the investigations comprise model experiments, ship trials with the associated theory and research in connection with current warship design, new construction and conversions or modifications to H.M. ships on service. Special problems are also investigated, including hydrodynamic aspects of underwater weapons. Additional facilities and new methods of approach have been called for, but these all derive from the foundations so securely laid by a great pioneer.

Facilities

Experiments continued at Torquay from 1871 until 1885, when in accordance with the terms of the lease the equipment was dismantled and the waterway filled in. Contemporary records indicate that there was no doubt as to the necessity of continuing the work, and the only problem was to decide on a suitable site and equipment. The site selected was in the Haslar Gunboat Yard, and a longer tank than at Torquay was provided with more permanent equipment. This facility, now known as No. 1 Ship Tank, has been in continuous use since it was completed in 1887. A major change was the provision of a wide carriage which spanned the full width of the waterway, in lieu of a narrow carriage running on overhead rails. This carriage remains substantially as built nearly seventy years ago. A feature is that the members of the structural trusses are thin wooden box girders. The structure is remarkably rigid and light and yet successfully carries a large load of apparatus at its centre. The fact that it is still in active use is a wonderful tribute to the design and workmanship, but it must be regretfully stated that owing to fair wear and tear, arrangements are now in hand for its replacement. Plans are also well advanced for an extension of length of the waterway by 100 ft to provide greater carriage speed and a complete cycle of oscillations in wave tests.

It became evident about thirty years ago that the volume of investigations called for was far beyond the scope of one tank. Additional and more modern equipment was necessary and proposals were formulated for a larger tank and a faster carriage to suit the developments of fast ships of various types. The necessity will be appreciated when it is recalled that at the time No. 1 Ship Tank was planned, the largest ship in the Navy was H.M.S. *Trafalgar*, about 345 ft long, of 11,900 tons displacement, and 16 knots speed. Eventually the equipment, known as No. 2 Ship Tank, was completed in 1932. The provision proved even more timely than was foreseen. Without the additional facility it would not have been possible to have carried out the work required during the last war.

The next facility to be completed was No. 1 Cavitation Tunnel. The Director of Naval Construction recommended this provision to the Admiralty in 1937 to meet the requirements of the rapidly expanding warship programme and the development of fast large propellers. The equipment was completed four years later.

The tunnel was found invaluable for investigations arising out of rapid wartime developments. It was apparent that all the requirements could not be met by one tunnel and proposals were formulated for an additional and larger tunnel. We were fortunate to find in Germany at the conclusion of hostilities a suitable tunnel that had only recently been completed. It was transferred to Haslar, and later when funds were allocated it was erected in place, and the building to house the equipment is now approaching completion. This item is known as No. 2 Cavitation Tunnel.

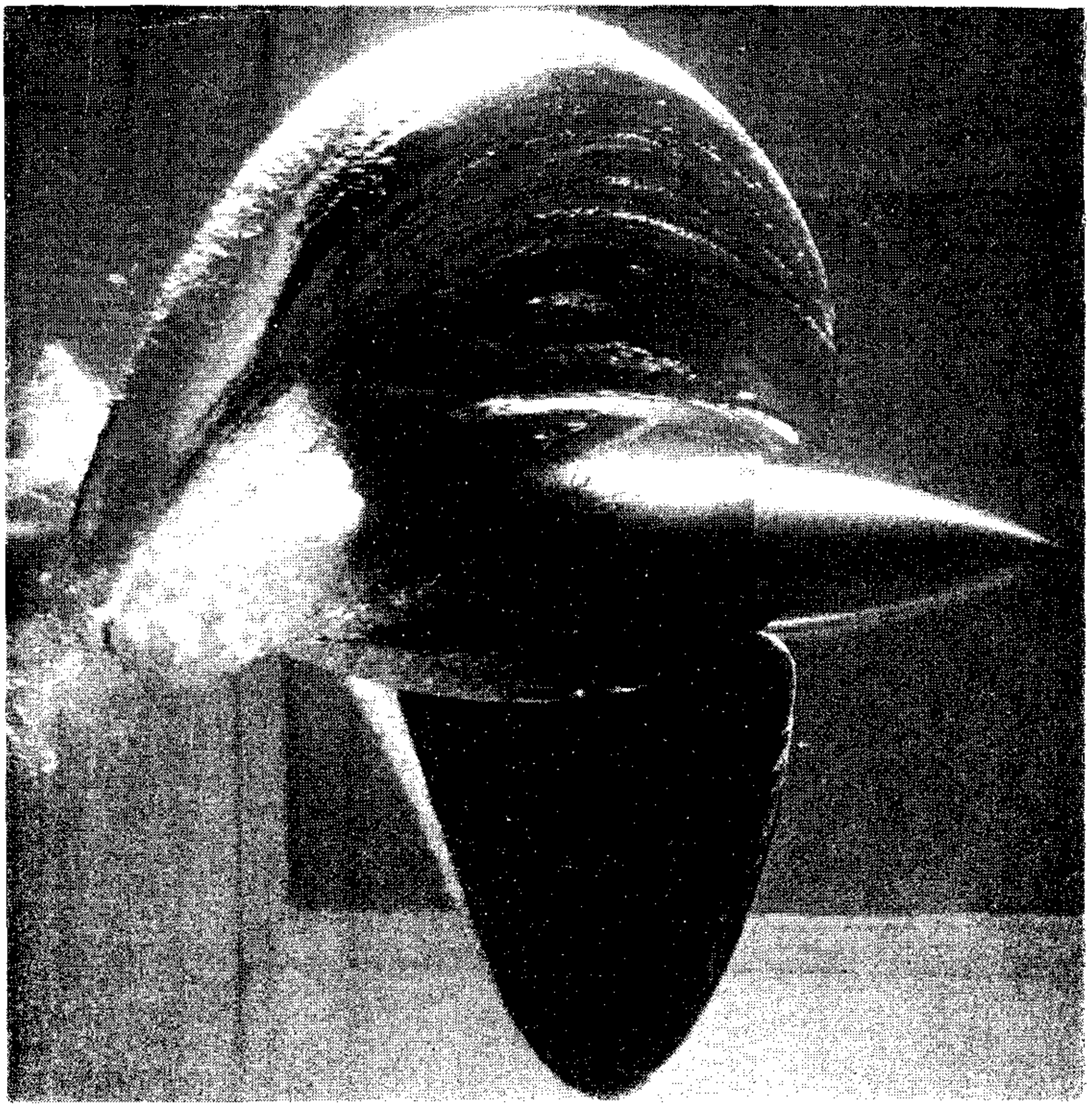


FIG. 2 (a)—PROPELLER CAVITATION. WIDE BLADED PROPELLER

Propulsion

The object of the investigations under this heading is to obtain the best shape of hull lines and the best shape and position of the appendages, together with the optimum design of propellers, both for maximum full speed and maximum endurance at cruising speed. This is achieved by testing models first of the hull alone, then with appendages added, and finally with propellers fitted. Requirements for cruising and full power performance are often conflicting and the relative importance attached to each affects the design. Bilge keels, rudders, shaft brackets, shafts, docking keels, and other appendages are secured successively in position on the hull of the final model and the resistance of each separately determined. Prior tests are made to ascertain the alignment of relevant items to the flow to reduce the resistance to a minimum. For this purpose the direction of flow of water at and near the hull is determined from the angles taken up by small vanes mounted on axes passing through the model. Importance is attached to the shaft brackets to reduce interference of water flow to the propellers as well as to ensure minimum resistance. Shaft bracket flow experiments are made, both with propellers working and removed respectively in order to isolate the separate effects of hull and propellers. Generally the influence

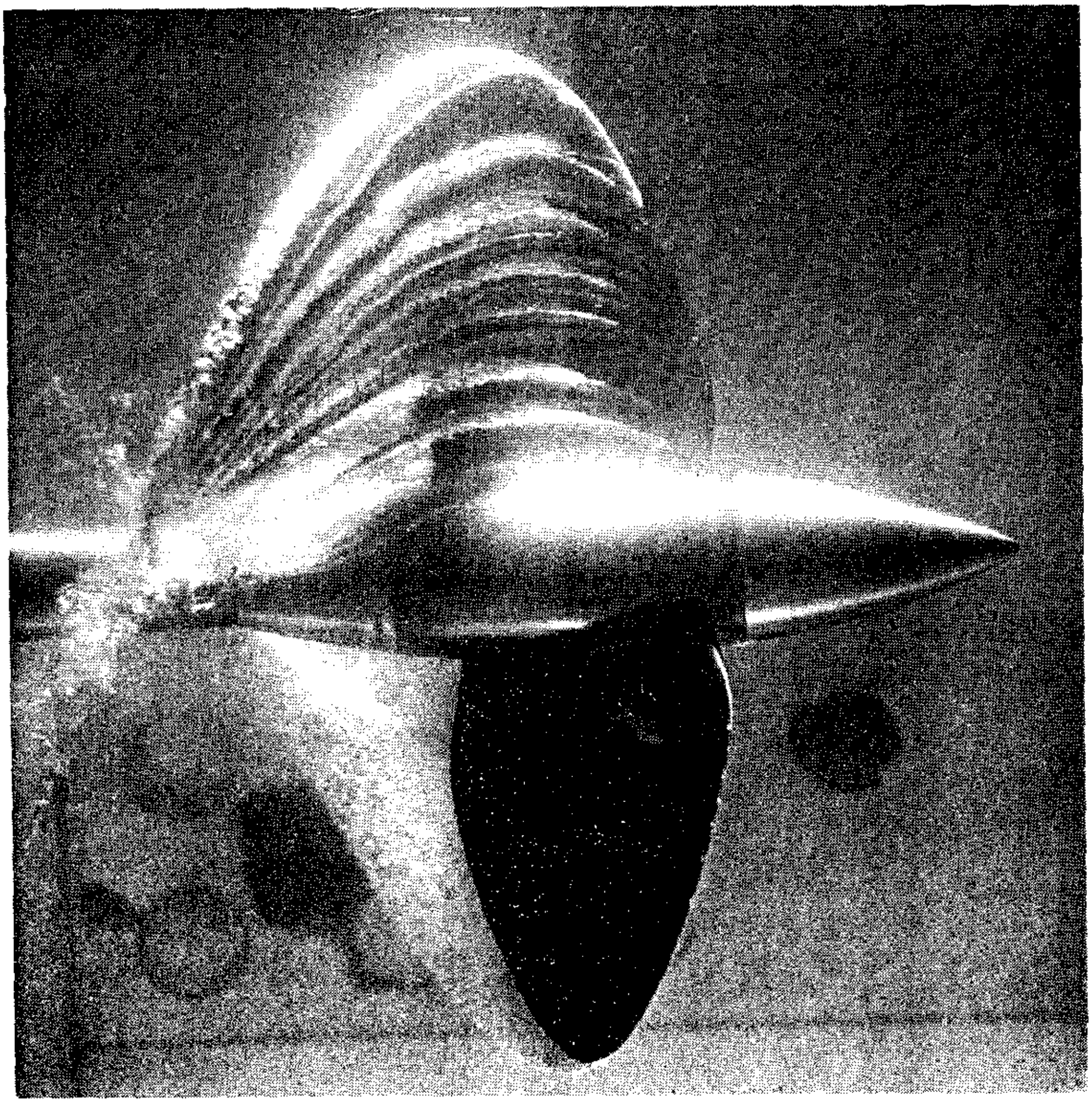


Fig. 2 (b) Narrow Bladed Propeller
Cavitation Number O 0·222 : Advance Coefficient J 1·253

of the propellers on flow direction is small if not negligible. One of the earliest steps in design is to determine the diameter, pitch, and blade area of the propellers, as these are the major features influencing efficiency. This is considered in conjunction with optimum shaft and ship speeds. The way is then open to prepare the preliminary drawing of the hull lines, special attention being given to propeller clearances to avoid vibration and cavitation. Frequently the problem is to arrange for the largest possible propeller that can be fitted. Following resistance tests as described above to include a model or models with modified lines, if improvement is expected inner drive propeller tests are carried out to determine the hull efficiency elements. The procedure is to cover a wide range of revolutions for each of the series of speeds of advance within the operational range. Hull efficiency elements appropriate to the model self-propulsion point are then determined over the speed range from curves. The detailed design of propeller is then prepared and cavitation tests arranged on a model, having regard also to erosion and vibration. Cavitation also promotes noise which can lead to hydrophone detection by the enemy and this aspect receives careful attention. Figs. 2 and 3 indicate one important lesson that can

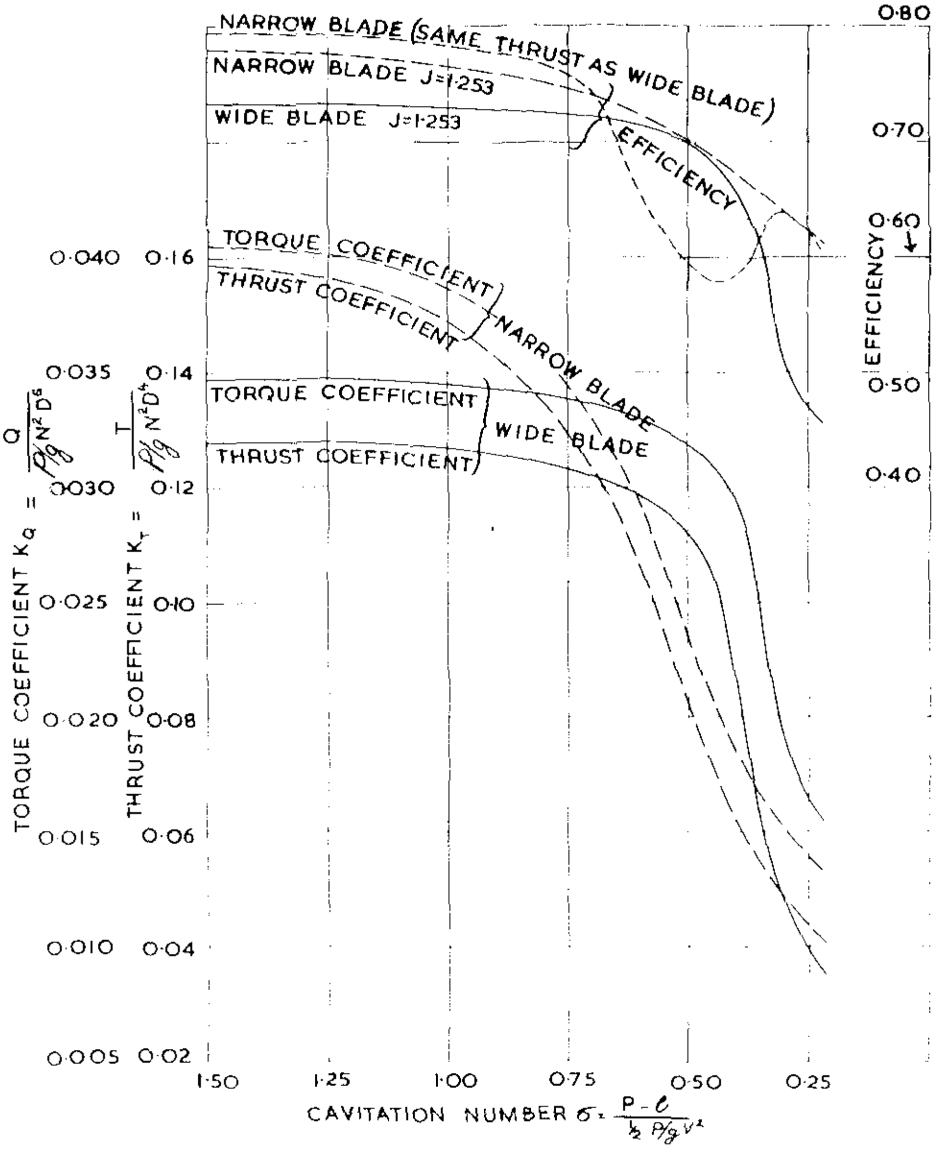


FIG. 3 —VARIATION OF PROPULSION CHARACTERISTICS WITH CAVITATION NUMBER

be learnt from tunnel tests. The narrow propeller is more efficient at high cavitation numbers when there is little or no cavitation, and also at very low cavitation numbers when the whole of the backs of the blades of each of the two models is covered with bubble cavitation. The particular models were for the speed record craft *Bluebird*. The wide propeller was more efficient between speeds corresponding to about 32 and 50 knots, but the narrow propeller showed to appreciable advantage at higher speeds up to the maximum of test with some indication both from the trend of the results and theory that the improvement would be maintained at greater speeds.

William Froude attached great importance to consistency and this was fully appreciated by his son R. E. Froude. The following account of experience with standard models emphasizes their wisdom and foresight. It was found from the first experiments at Haslar in April 1887 that the resistance of the model was much less than seemed plausible. It was decided to remake and try a model which had been carefully tested at Torquay, and a model of H.M.S. *Iris* was selected for the purpose. This model was tested in May 1887 with the result that to bring the resistance curve into agreement with that obtained at Torquay it was necessary to assume that the skin friction of the water in the Haslar tank was nearly 7 per cent less than that of the water in the Torquay tank at the same temperature. Subsequent trials of the *Iris* model at intervals showed a gradually increasing resistance, and by the end of June 1887 it was about equal to that recorded at Torquay. The gradual increase in resistance quality of the water was corroborated by the results of repetition experiments with other models. In order to avoid any serious error it was decided to follow the expedient already adopted, namely regular and frequent tests of a standard model. During the early experiments another circumstance indicated a difference in character between the water at Haslar and Torquay. This was the tendency of the water to deposit minute air or gas bubbles on the surface of the models which at moderate speeds did not exfoliate, but adhered to the surface and considerably increased the resistance by variable amounts. This trouble was not experienced in the Torquay tank. Subsequent experience confirmed that the phenomenon is seasonal and is apparent from spring to autumn, when the water temperature exceeds about 50° F. An appliance for lightly brushing the surface of the model immediately before each run was installed in No. 1 Ship Tank in 1887, and similar provision was made in No. 2 Ship Tank on completion.

Generally the change in resistance of the standard model during an annual cycle is small and the temperature correction, namely 3 per cent decrease of skin-friction for each 10 degrees Fahrenheit rise of temperature is well confirmed by the tests.

Abnormal changes in the resistance quality have been recorded on comparatively rare occasions.

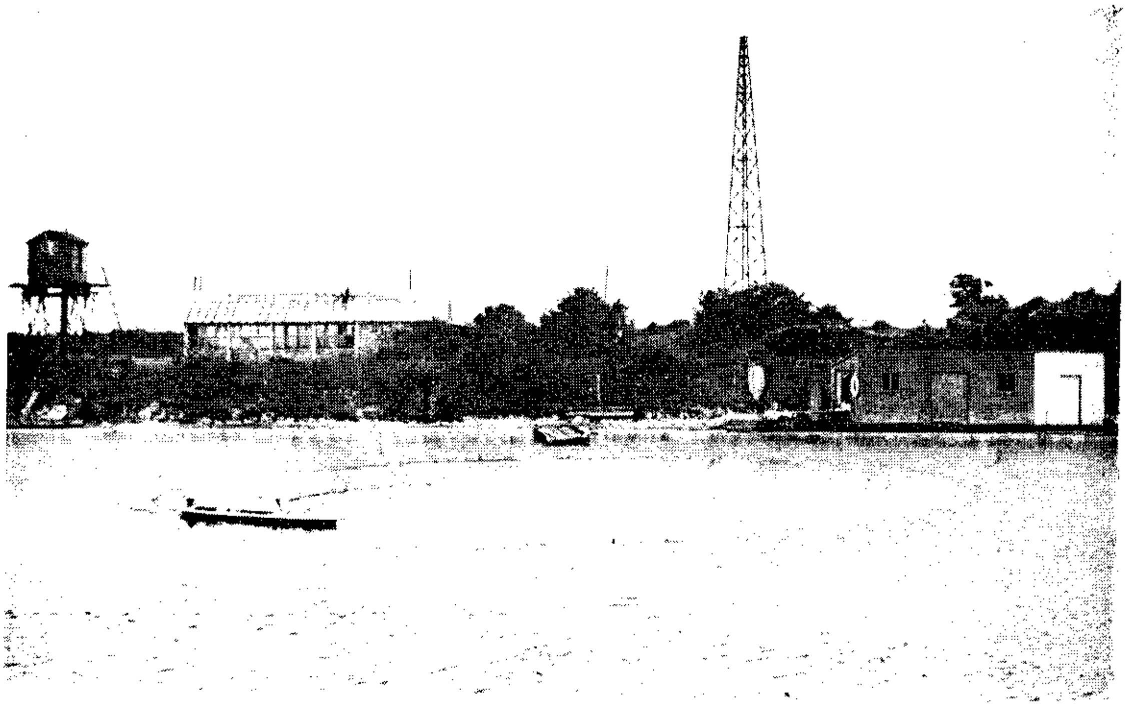
The character of these abnormal variations has been very much the same, namely, a more or less gradual change to the maximum and a gradual restoration to the normal value, the total period concerned being about two to three months.

The resistance of the standard model when tested in No. 2 Ship Tank has been fairly steady and equivalent to a reduction of about 5 per cent of the skin friction. It is not unreasonable to expect that the resistance would be less than in No. 2 Ship Tank, on account of the greater size and consequential increased freedom from side wall and bottom interference.

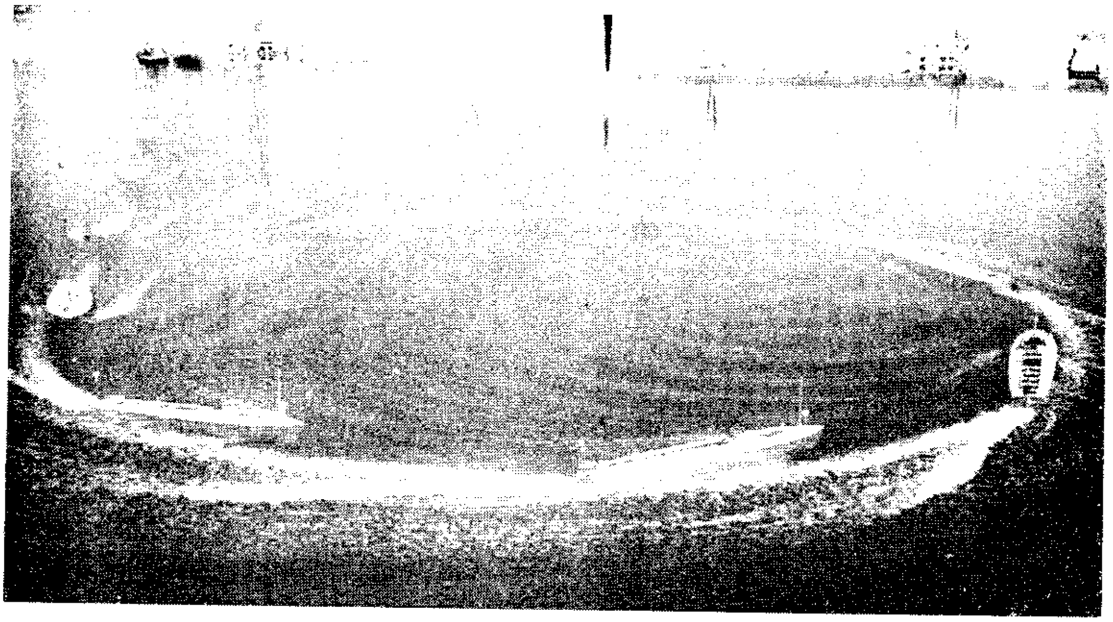
Profiting by this lesson, one of the earliest model propellers tested in No. 1 Cavitation Tunnel has been retested from time to time. No really significant change in propulsion characteristics has yet been measured at all analogous to the variations with the standard model hull. Nevertheless the tests of the standard model propeller have contributed much to the detection of minor irregularities in the apparatus.

Manœuvring

Occasional investigations only on certain aspects of manœuvring were called for in the past, but the work for many years was largely confined to the determination of three component forces on a model controlled on a straight course. Rudder torque and force were also measured for guidance in the design of steering gear and rudder stock. The tests were informative as regards directional stability and the effect of the reaction of propeller race on hull and rudder, but only gave indirect guidance on the turning qualities generally. Encouraging improvements were obtained from turning tests on freely propelled models commenced about twenty years ago. War experience emphasized the necessity



General Arrangement



Photographic Record of Path

Fig. 4 Model Turning in Artificial Lake.

of quick steering, manœuvring and acceleration from rest and underway for attack, especially for hunting submarines. Manœuvring of propelled models about 20 ft. long is investigated in a deep lake. The hulls are generally made of wood and carvel-built to light construction, having regard to the necessity of the provision of weight and space to accommodate measuring apparatus and propelling equipment. A fair margin of disposable weight is also necessary for ballast to reproduce the stability and moment of inertia of the ship. The model is driven by electric motors supplied by batteries. Time switches are provided for control of starting and stopping and for operating the steering gear with limit switches for the prescribed angles of rudder. The rate of movement of the rudder corresponds to that of the ship. The turning path is determined photographically and the records include time, angle, and rate of movement of rudder, shaft speed, and angle of heel. Speed of advance is deduced from the turning path and checked by calibration of the shaft speed. Electronic dynamometers are fitted in some models to record the transient torque and force on the rudder. A small laboratory and a photographic tower are provided (FIG. 4). Free turning tests are also made in No. 2 Ship Tank, but the length of the model must be restricted to about 6 ft. on account of the limited width of waterway. The small model has the great advantage of economy in effort and the quick assessment of steering qualities in the initial stages of the design so that improvements can be timely embodied.

The three-dimensional freedom of submarines presents an involved problem. Complications are introduced by the free surface and the consequential change in forces with speed and immersion. Component forces can be determined on a straight course in a ship tank, but for realistic results stability derivative tests on a rotating arm are necessary. Plans are in preparation for a manœuvring tank suitable for test of models of surface ships and submarines. The design provides for the generation of waves of mixed components in two directions, which will permit a realistic investigation of seaworthiness with coupled motions, the more so as the model can proceed on any line of bearing.

Seaworthiness

Many examples could be quoted illustrating the importance of weather in naval operations. Reduction of rolling was one of the problems so brilliantly investigated for the ships of his day by William Froude. Sustained speed and steadiness at sea are of paramount importance for modern warships. Pitch, heave, and roll are measured and full consideration given to damping the motion. It is important that decks and operating positions should be as free from sea and spray as possible in adverse weather. Fans are brought into play to determine means for avoiding spray blown inboard by a cross wind. Denny-Brown stabilizers are fitted to many of H.M. ships, and model tests in the ship tank and cavitation tunnel play a part in determining the size, shape, and arrangement of the fins.

A wave generator is provided in each tank, that in No. 1 being basically as first fitted nearly fifty years ago, although the driving arrangements have been considerably improved with steady control and adjustment for waves of different sizes. Regular waves up to a length of 40 ft and height 2 ft can be generated thus reproducing on the model scale the full range of wave size on the oceans. The importance of investigations in waves needs no emphasis as regards the bearing on hull form, loading, freeboard, and other factors and the Manœuvring Tank mentioned in a preceding paragraph indicates that, as far as the Admiralty is concerned, this type of research has an expanding role. Paradoxically perhaps, calm water tests also afford useful information on seaworthiness. Change of draught of models at speed is regularly measured. A large ship will sink by about 3 ft at the bow and 2 ft at the stern at high speed. On the other hand, the bow of a destroyer rises by about 2 ft, although the draught increases aft by about 5 ft. The difference is, of course, largely due to the length of the transverse wave which is less than that of the large ship but greater than that of the destroyer. Change of draught at speed is greater in shallow water and can become critical at certain speeds. This is of operational interest when, for example, bombarding an enemy coast, and has been investigated accordingly.

Vibration

Ten years ago the Director of Naval Construction advised the Board of Admiralty that war experience confirmed that improved facilities were necessary for investigating vibration of H.M. ships. The general trend had been in the direction of increased speeds under all conditions of service, with higher machinery powers per propeller shaft. This, in conjunction with the increased number and sensitivity of instruments required for accurate gunnery and other purposes, including radar, necessitated that ship vibration should be further reduced in new construction.

Most vibration in H.M. ships, especially with turbine drive, is propeller excited either hydrodynamically or from imperfections in propeller balance. The latter is guarded against by precision manufacture, which has been refined in recent years as a result of experience in cavitation and other fields. The factors governing propeller induced vibration have long been recognized, and the lines of a ship and shape of appendages are designed to avoid eddies, and to lead to as small and uniform a wake as possible. The propellers are arranged well clear of the hull and appendages accordingly. There is still much to be learnt concerning the velocity gradient in the boundary layer and trials on a ship have been arranged as one line of approach.

If the natural frequency of the propeller shaft system is resonant with that of the propeller blade beats, axial vibration will result. The amplitude should not exceed 0·025 in., in order to avoid serious wear on the flexible couplings between the gear-boxes and the turbines and on the other machinery items. Propellers with five blades and also with four blades have been fitted to some shafts of certain classes, in lieu of propellers with three blades, with very satisfactory results.

A small vibration laboratory has therefore been provided to accommodate the staff and apparatus. One of the first duties was to obtain the necessary equipment. Existing mechanical vibrographs were improved and additional instruments of new type obtained. Special instruments have been provided for accurate recording of low frequency vibrations free from resonant excitation which leads to excessive readings. A vibration table is available for calibrating the recorders.

Comprehensive vibration surveys are carried out during all first of class ship trials. Other trials are arranged to investigate any objectionable vibration reported at sea. Although hull vibration may be slight, resonant response may be excited in local items such as a mast with the heavy radar and wireless aerials or in director towers. Vibration generators have been used with success to ascertain the natural frequencies of fundamental and higher modes of vibration and the forces exciting vibration at sea. These trials are carried out while the ship is in harbour and are accordingly not subject to restrictions which may obtain when the ship is at sea.

It may also be mentioned that good progress has been made with advance prediction of resonant frequencies as described recently by Sir Victor Shepheard the Director of Naval Construction.

Ship Trials

Accurate measurements on ship trials are essential to afford a reliable basis for improvement in the design of H.M. ships. A comprehensive programme is arranged for each first of class ship and the trial records for which the Admiralty Experiment Works are responsible comprise progressive measured mile speed trials, turning, manœuvring and a vibration survey. Opportunity is also taken to record pitch, heave and roll and to observe behaviour of the ship generally in adverse weather and note any features that are affected by sea and spray.

Some ships are fitted with stabilizer fins and additional trials are involved to determine their effectiveness. Other trials include the measurement of bollard pull and of towing pull over a range of speed and machinery power for such classes as minesweepers and tugs. Fast patrol boats present special features on account of the wide speed range and the large dynamic lift. In addition to the other measurements, running rise and trim of the boat is carefully ascertained, as this is important at the hump and higher speeds for seaworthiness as well as propulsion. Hull pressure and slamming accelerations are also measured for certain boats. Progressive measured mile speed trials have been carried out on some ships with alternative sets of propellers, and the series for two classes of destroyer have been of rather large scope. Glass viewing ports have been fitted in the stern for observing and photographing propeller cavitation.

The extent to which the trial programme has grown may be appreciated from the statement that manœuvring trials now include about fifty complete turns through 360 deg, covering a wide range of approach speed and rudder angle, whereas formerly six turns were considered sufficient. It may be added that manœuvring trials include full tests of the rudder and steering gear and also careful measurements of the acceleration and deceleration distances. The system of analysis of all trials is directed to a ready assessment of the validity of scale corrections from model tests as well as the standard of ship performance.

Apparatus

A wide range of measuring apparatus is now necessary and it is tempting to describe the items in detail, but this would require much greater space than can be found in this paper. The resistance dynamometer of No. 1 Ship Tank was transferred from Torquay and continued in regular use until a few years ago, when it was replaced by a modern apparatus. This record of eighty years' accurate service speaks for itself as to the high standard of design and workmanship. The original propeller dynamometer also saw very long service at Torquay and later at Haslar, but has been replaced by a motor-driven apparatus. Similar dynamometers but of greater capacity are on No. 2 Ship Tank carriage. A feature of the instrumention is the ' little logs ', which are located well ahead of the experiment carriage. Their purpose is the measurement of the water current and hence the necessary correction to the speed as measured over the ground to obtain the true speed of the model through the water. The arrangements are much the same in principle as for the first logs at Torquay, but the details have been improved. The determination of carriage speed from autographic records of distance and time has now given way in No. 1 Ship Tank to the measurement by a Cintel decimal counter chronometer of the time of transit past two photo-cells 166⅔ ft apart. This method combines accuracy with economy of staff. Three component force dynamometers are provided for tests of hulls and control surfaces generally. In most cases the apparatus for measuring steady forces is of mechanical type with electrical auxiliaries, but good use is made of electronic applications for transient measurements. This important advance has opened a wide field for measurements that could at best only be approximated to formerly, and a small electronics laboratory is provided for the staff to develop and calibrate the various items concerned.

Ship trial apparatus includes among other items ship motion recorders generally of gyro type (although pendulum instruments still find occasional useful application), bearing recorders for turning path, and instruments for measurement of hull and propeller roughness. A difficulty with ship motion is the effort involved in analyzing the large accumulation of records. Statistical recorders are under development for ready information on displacement, velocity, and acceleration. A calibrating laboratory is provided suitably equipped for dealing with ship trial instruments, for the assembly and calibration of apparatus for model tests, and the equipping of models complete with instruments for special tests.

Photography now finds wide and increasing applications. Single flash photographs of propeller cavitation are taken with an exposure of 25 microseconds for the model and 60 to 500 microseconds for the ship. These fast speeds involve the provision of powerful lighting with carefully controlled flash. Investigations on ship motion are greatly assisted by photography, and cine films of model hulls when proceeding at various speeds, in uniform waves of different lengths and slopes, afford permanent records of the behaviour, including dryness. Any local features that may promote wetness are investigated and modifications arranged for improvement. High-speed cinema views of cavitation are also invaluable. The present limit is 15,000 frames per sec., and although sufficient for some requirements, the long term aim is to trace the life history of bubbles, and this will probably require a six-fold increase in speed, which in turn calls for special technique, the necessary arrangements for which are under development.

Model Manufacture

The process of rapid and accurate reproduction of model hulls in paraffin wax initiated by William Froude has remained unaltered in essentials since his day. The original shaping machine at Torquay, although still available as an exhibit, was replaced when the establishment was transferred to Haslar by a larger and more convenient machine with horizontal in lieu of vertical traverse tables. This in turn was replaced in 1932 by a machine similar in principle, but of greater capacity and improved in detail. (FIG. 5). Satisfactory production of models depends very largely on the preparation and casting of wax. New supplies are first melted down and cast into buckets to solidify. The ingots are again melted, cast and solidified, the process being repeated six times. Four per cent of beeswax is added at the last melting. This procedure is necessary for a homogeneous casting. In recent years 10 per cent of ceresin has also been added. This was arranged following a series of tests, including measurement of elastic modulus on samples with varying amounts of ceresin. The results were promising and one or two models were made with the ceresin addition. Experience confirmed that stiffness was increased and the objectionable small hog was avoided in one model and reduced in others. Less tension was required in the truss wires accordingly. A further advantage is the elimination of porosity. Wax models are not satisfactory for tests in waves over any prolonged period on account of the liability to deformation and damage and also the limitation of disposable weight. Light wooden models are employed for seaworthiness and also for manœuvring experiments, the necessary machine equipment being provided for the purpose. Developments in plastics offer prospective advantages, one application being for submarines and a small experimental model for this purpose is being investigated. It should be emphasized, however, that paraffin wax is so overwhelmingly superior as regards economy and quick production, that models of other materials are only considered when the experiment requirements cannot be met by a wax hull.

The traditional process of making model propellers of a low melting point white metal, conveniently cast in a plaster of Paris mould, is still followed for small models. Precision standards and stronger and stiffer material are necessary for the large models required for cavitation and other tests. A pattern blade is first made in white metal, cast with a machining allowance in a plaster mould. The propeller is then moulded in loam and cast in manganese bronze or aluminium-silicon alloy as required. Temperature control by pyrometer combined with careful foundry practice is important for the elimination of blowholes, particularly in the light alloy castings. The propeller is machined on the

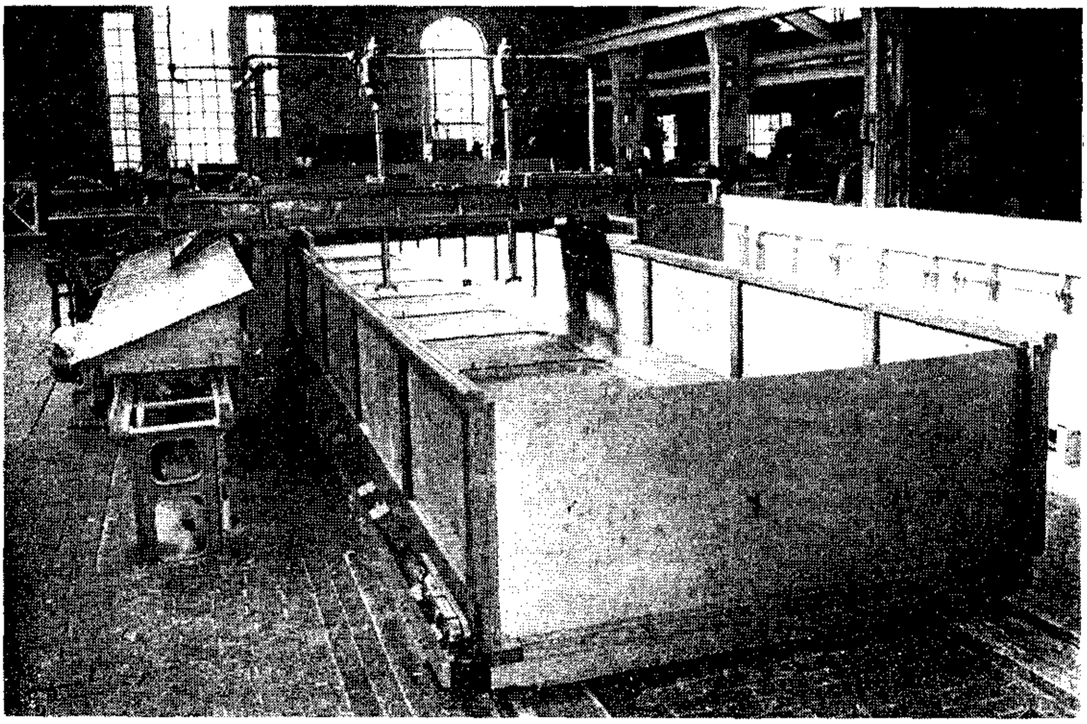


FIG. 5—MODEL SHAPING MACHINE

face, finish being by successive grinding and buffing. Any small surface holes are stopped by a cold weld process. The backs are finished to shape, determined by small bore drillings to micrometer thickness, the surplus material being removed by grinding followed by buffing. In order to meet the production requirements of the expanded establishment, model propeller manufacture is now concentrated in a propeller laboratory provided with a foundry, machine shop, grinding, welding, and strickling bays.

General

We have seen that the Admiralty Experiment Works, Haslar, originally planned to meet the requirements of the comparatively slow and small ships of the Victorian Navy has been adapted and expanded to meet the exacting needs of the fast and large ships of the modern Elizabethan Navy. Aircraft carriers, battleships, cruisers, destroyers, frigates, submarines, mine-sweepers, landing craft, fast patrol boats, and non-combatant vessels illustrate the variety of present day classes, each with problems for the model experimenter. Gunnery control, radar, and weapons have complicated the investigations. The slow reciprocating machinery of last century has largely given way to the steam turbine, the internal combustion engine, and recently the gas turbine, to add to the complexities of the propeller designer. Investigations as described in the preceding paragraphs must be progressed in parallel, as it is essential that one quality of the ship should not be improved at the expense of other qualities of comparable importance. Many special problems are also investigated and mention may be made as examples of air breakwaters, floating breakwaters, waves on beaches, and circulating water systems, including the shape of inlets and outlets. The latter includes pressure and flow measurements as well as propulsion. Tests in the cavitation tunnel have played a part in developing the shape of aircraft wings. Work on model anchors has been conducted and a number of improved mooring anchors have been ordered. Striking economies effected in the cost of moorings exceed many times that of the small anchor tank and staff. This saving is cumulative and provides a convincing answer to those who may question the cost of research. It is remarkable that the system initiated by our pioneer has stood the test of time with the consequential wide developments.

Not the least of our debts to William Froude is the training of his gifted and devoted son Robert Edmund. He assumed his father's mantle at a comparatively early age, and his distinctive genius was soon manifest at Torquay and later at Haslar. He, like his father, achieved much with comparatively simple means, and this is reflected in the equipment of No. 1 Ship Tank at Haslar, which remained substantially unaltered until his retirement in 1919 at the ripe age of 72, rich in achievement. He had been associated with his father from the start of the work at Torquay, and so completed a period of about fifty years in the Admiralty service. An adequate appreciation of R. E. Froude's work is outside the scope of this paper, but mention may be made of his outstanding work on methodical series propellers and the associated theory. He was the first to clarify the hull efficiency elements expressing the interaction between hull and propellers, and paid early attention to hull form and the effects of systematic change of shape. He completed the first systematic investigation on ship motion and resistance in regular waves no less than fifty years ago. The constant system of notation which he evolved has systematized and simplified the calculations associated with model experiments. It is not surprising that it has continued in regular use since its inception at the beginning of the work at Haslar.