INSTITUTE OF MARINE ENGINEERS

INCORPORATED.

SESSION 1915-16.

President: SIR ARCHIBALD DENNY, BART., LL.D.

VOLUME XXVII.

The Screw Propeller.

BY SIR ARCHIBALD DENNY (President).

READ

Tuesday, September 7, 1915.

THE first screw propeller was probably a complete helix, but it was found that a complete helix was disadvantageous, and that a small portion of it was all that was necessary. A two-bladed propeller is derived from a double helix, a three-blader from a treble helix, and so on.

The important particulars of the screw propeller are usually stated as follows:—D is the diameter, P is the pitch (that is the distance which would be travelled by the screw without slip in one revolution, or the length of the generating helix) and the ratio projected area of all the blades to the disc area is very important and is usually written $\frac{\text{proj}}{\text{disc}}$. The ratio of P to D, the pitch ratio, has an important bearing upon efficiency.

Suppose for the moment that the screw is working a long way astern of the ship and that v is the speed of the ship, now to drive the ship forward the propeller must drive a column of water aft.

Let the speed of water in the propeller race be V, then (V – v) is the speed imparted to the water by the screw, or is the speed of the slip. You must have slip in order to move the vessel, how is it then that engineers find that sometimes they get negative slip? that is what I propose to explain. I may, however, say at once that real slip, such as you might get under the conditions aforementioned, is a very different thing from the apparent slip, which is what the engineer gets on trial trip, or at sea; because in actual practice the propeller is fitted fairly close to the stern of the vessel and then other conditions arise.

A vessel moving through the water experiences resistance, due in part to the frictional resistance of the water on the immersed surface, which causes the water to be dragged in a forward direction, and hence at the stern there is usually a following wake, in other words, the water is not moving towards the screw with the speed V, but with some smaller speed. The wake effect is not, however, solely due to frictional resistance, but there is, at anything but very low speeds, the orbital motion of the particles of water due to wave-making, and there is also the effect of stream line motion.

Let v be the speed of the following wake with reference to still water, then the speed of advance of the screw through this is not v but $(v - v_1)$. Now the usual way of stating slip-ratio is $\frac{V - v}{V}$ where V is equal to P × R, P being the pitch and R the revolutions per minute. But the speed of water flowing towards the screw is now $(v - v_1)$ instead of v, and hence the real slip is greater than the apparent slip of a screw working near the stern of a ship. When stating the speed of the screw as P × R, it is assumed that the pitch of the driving face of the screw is the real pitch, but this is not necessarily so, in fact it is seldom so.

Our experimental tank was opened in 1883. At first we dealt only with ship models, but as soon as possible we also began experiments with model screw propellers, both behind models and without models in front of them. We observed curious differences, between real and apparent slip, and we thought that some light might be thrown on this by experiments with a series of screws and a corresponding series of discs and sectors of the same diameters.

Early in 1898 we tackled the work seriously and diagram (1) shows one set of screw propeller results. These screws were all of the same diameter, number of blades, projected to disc area, thickness at the root and general outline, but while the pitch of the driving face of each screw was uniform, the pitches of the different screws varied from ·5 of foot to 2 feet. These were driven along the tank without any model in front of them—driven in the open as we call it—and were driven at different rates of speed of advance and at progressive r.p.m. (revolutions per minute) for each speed. In diagram (1) the speed along the tank was 500 feet per minute. The diagram is plotted on a base of slip ratio (assuming the pitch of the propeller to be the pitch of the driving face) and thrust, revolutions and efficiency are the ordinates.

Now with a slip ratio of zero, that is to say when P × R equals 500 feet, there should be no thrust. This is far from being the case for a screw with ·5 of a foot pitch, the thrust instead of being zero, is 8 lbs. and the efficiency is nearly a maximum, while the efficiency curve does not strike the base line until the slip ratio is nearly minus 20; that is to say, instead of the real pitch being ·5 feet, it is ·588 feet at zero thrust. Similarly, the screw with one foot pitch had a thrust at zero slip ratio of nearly 1 lb., and the efficiency is very considerable. In the 1·5 foot screw on the other hand, the real pitch is slightly finer than the pitch of the driving face, also in the case of the 2 feet pitch screw.

I do not know whether this was generally known by marine engineers at that time, at any rate it did not seem to have been so. In a recent publication, the discrepancy between the real pitch and that of the driving face has been recognised and referred to, but it is there assumed that the real pitch exceeds that of the driving face by a constant percentage. We have found that this is not so, and that the difference varies with a number of factors. Generally, however, it may be stated that if the blade sections be symmetrical, a coarse-pitched propeller has a slightly finer real pitch than the pitch of the driving face, and a fine-pitched propeller has a considerably greater real pitch than that of the driving face. When the pitch ratio of the driving face is about $1\frac{1}{2}$, the pitch of the driving face is then identical with the real pitch. The discrepancy between the real pitch and that of the driving face varies, however, with speed of advance, with the width and shape of the blade and with its thickness, and if the section of the blade be not symmetrical about its centre, the real pitch

RESULTS OF MODEL SCREW PROPELLER EXPERIMENTS IN OPEN WATER—SPEED 500 PER MIN. TIPS IMMERSED HALF THE RADIUS.

PARTICULARS OF PROPELLERS.

Diameter	·738′	·738′	·738′	·738′
Pitch of Driving Face	·5′	1·0′	1·5′	2·0′
No. of Blades	2	2	2	2
Total Projected Area	·0704	·0704	·0704	·0704
Total Projected Area / Disc Area	·164	·164	·164	·164
Thickness at Root	·025′	·025′	·025′	·025′

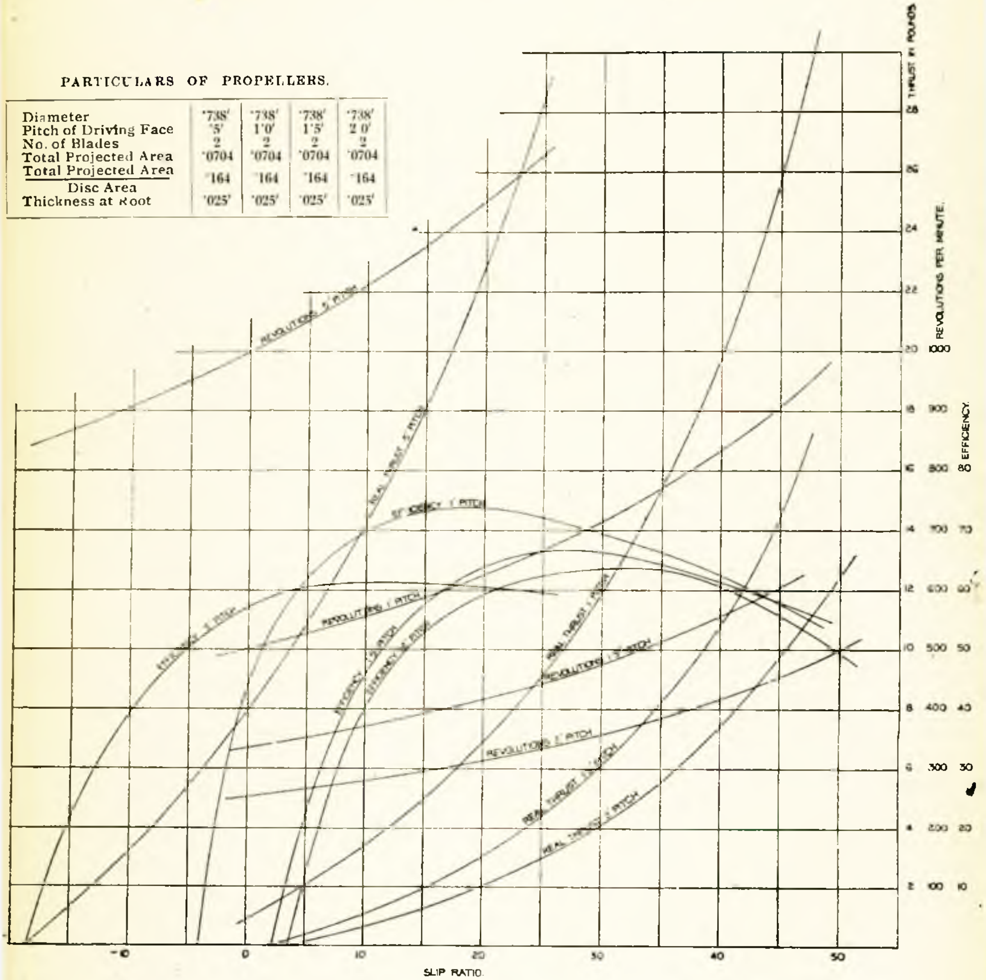

Diagram I.

may vary greatly from the face pitch. I am also of opinion, it is not correct to take the real pitch at any particular speed of advance as being that pitch at which you get no thrust.

The question therefore becomes exceedingly complicated, and the results of our experiments with screw propellers suggested a series of experiments to ascertain the effect of revolutions alone. It was thought that light might be thrown on the kind of variation of pitch due to thrust by experiments on flat sectors without pitch, and also that such experiments might help the study of the effect of revolutions on the amount of water acted upon by screw propeller blades of certain widths and varying revolutions as compared with the complete disc; that is to say, it was desired to study the effect of revolutions *per se* upon the efficiency of screws. We therefore tried in 1898 and 1899 complete discs of different diameters, and sectors of the same discs of varying proportionate areas, a sixth, a fifth, a fourth, and a third.

Diagram No. 2 shows the result of a series of tests of such a disc and of such sectors, all of the same diameter as one of the previous sets of screws, made as thin as possible, and advancing at 500 feet per minute. In order to eliminate the effect of eddies round the periphery of the discs and sectors which might be caused by the two square edges of the plate, the edges were rounded as shown, but the sectors of course had still no real pitch.

This diagram shows the resistance of the complete disc and sectors when advancing at 500 feet, but driven at different revolutions. The lower series of curves show the turning moments, the upper series of curves show the resistances. The diagram is of extreme interest, and it will be observed that for the complete disc the resistance increases with increase of r.p.m. When the sectors are not revolved, the resistances in proportion to that of the whole disc are practically in proportion to their respective areas, showing that eddy-making had either the same proportional effect, or practically no effect.

When the whole disc was revolved the resistance increased, and doubtless the effect was as if the disc had been increased in diameter due to the centrifugal action throwing the water out beyond the edge of the disc, while the turning moment was roughly in proportion to the square of the speed, as one would expect, because it can only be due to surface friction. Quite another effect, however, is got with the sectors. The resistance at first increases very rapidly with increase of speed of rotation, but the turning moment, after a slightly more rapid increase than that of the complete disc, falls off, passes through zero and becomes negative over a considerable range of revolutions per minute, and the smaller the sector the greater is this range.

Curves of Resistance is pounds, and Turning Moment in ft. pounds, of a Disc and Sectors in terms of Revolutions per min. at a constant speed of advance in fresh water.

Diam. of Disc. and Sectors = ·738 ft.
Thickness „ „ = ·012 ft.
Speed of Advance = 500 ft. per min.

The Sectors have no pitch on either face, and the edges are sharpened.

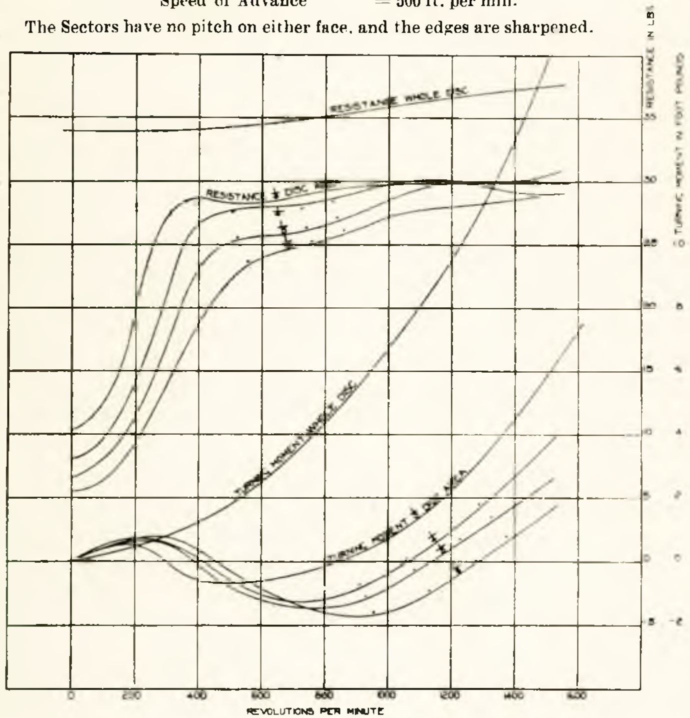

Diagram II.

I do not propose to study this diagram exhaustively, but it seems to show that while the sectors had no apparent pitch, they had a very real pitch when rotating. The shape of the resistance curve is interesting in this regard, as it would otherwise probably not have had the dip down as shown between 400 and 800 r.p.m. in the different sectors, alteration in shape begins where the turning moment curve crosses zero, and the curve is re-established where the turning moment curve re-crosses the zero line. The general shape of this curve would also seem to show that a flat sector, driven at an infinite number of revolutions, would probably have the same resistance as the complete disc, and that revolutions *per se* are an important element in screw propellers.

In making these experiments, we found that if the sector was started on the run down the tank, free, but not revolving, that it then remained non-revolving, and we simply got the resistance of the sector at no revolutions. But, if we started the sector on its run with an initial spin, but free from the cord which gave the turning moment, then the revolutions increased during the run, until they arrived at the point where the turning moment curve re-crossed the zero line of turning force; that is to say, the sector really became a screw with a certain pitch, and was rotated at a definite speed by being dragged through the water. It was found that this was true in whatever direction the flat sector was started to revolve. This is perhaps the best proof that the flat pitchless sector has a real pitch. This experiment can be repeated with a similar sector in an air current, produced, say, by a blowing fan.

The effect of revolving any of the sectors in water was to rapidly increase their virtual area, and the same virtual increase of area no doubt takes place in an ordinary screw propeller. It is for this reason that excellent efficiencies are got with slow turning large propellers, whose projected area to disc is low, say in the region of ·25, and this diagram also explains why increase of projected area to disc, at higher revolutions of screw propellers, has not the same proportionate effect as at lower r.p.m. These facts, I think, should be helpful in the study of cavitation.

An explanation of why the turning moment curves of the sector rise more rapidly at first than that of the whole disc,—although the sectors have only a small proportion of the area of the whole disc—is that the sector has a real pitch very much less than that required to give no thrust or resistance, and thus drives the water forward relatively more than the disc does, and hence increases the relative resistance. This real pitch varies as the revolutions increase, until it drives water forward at a reduced rate with increase of r.p.m., thus the increased r.p.m. over a certain range requires reduced turning moment, and causes a corresponding reduction of resistance of the sector. That is why I have given it as my opinion, that real pitch does not remain the same throughout all revolutions and thrusts in the actual propeller.

Another way of stating this is as follows:—It will be seen from the diagram No. 3 that the turning moment of the sector thereon dealt with, and which has an area equal to one-third of

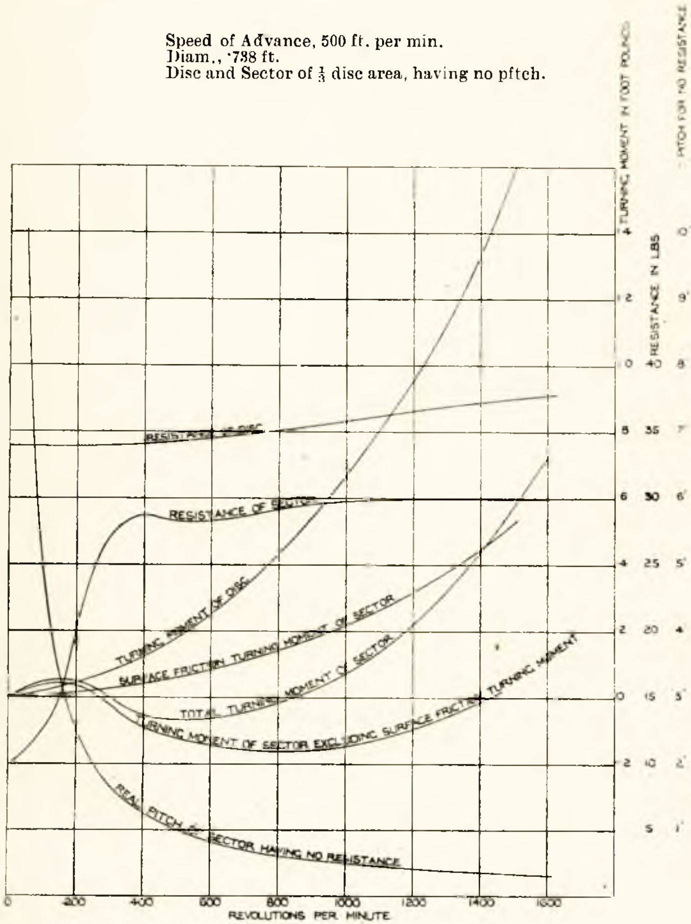

Diagram III.

that of the disc, has a negative turning moment over a considerable range of r.p.m., and if we deduct the turning moment due to surface friction (which may be assumed to be about one-third of the turning moment for the complete disc) we find that the turning moment due to the hydro-dynamic pressure on the sector blades, is very considerably negative between, say, 300 and 1,400 r.p.m., as shown by the curve. On the same diagram a curve of pitch for no thrust or resistance is given (pitch in feet equals $\frac{500}{\text{r.p.m.}}$). Now the apparent pitch of the sector is a constant; in fact, it has no pitch, whatever the r.p.m. may be, but the real pitch varies with r.p.m., and therefore it differs in varying degree from the apparent zero pitch with varying r.p.m., and it appears from the curve of resistance of the sector, that the difference between the real pitch of the sector and that required for no thrust or resistance is a variable, which at low revolutions is a very rapid variable. The difference becomes much less as the r.p.m. increase, but the change of curvature in the resistance and turning moment curves for the sector, shows that the real pitch of the sector changes at probably an irregular rate, with varying r.p.m. If it really remained a constant, or if it changed at the same rate as the pitch for no thrust, then we should always find resistance of sector increasing with increase of r.p.m., instead of sometimes being reduced.

The remarks I have made as to the following wake might be taken to mean that for any particular ship at any particular speed this following wake has a definite speed for all arrangements of propellers. This is not so. In the case of a single screw vessel, the wake is probably symmetrical on each side of the stern post, and what we get as following wake would be the same, whether the propeller revolved right-handed or left-handed, but in the case of twin-screws the wake percentage is different, depending upon which way the propellers revolve. Usually, propellers of twin-screw ships revolve either both inwards, or both outwards, at the top, but if the wake is taken from the model with inward revolving screws, and then taken again with the same screws revolving outwards, that is to say, reversing the screws from starboard to port, a different percentage would be obtained. It is for this reason that different hull efficiencies, different gross efficiencies, and different speeds for the same power, by revolving the screws outwards or inwards on the same ship are obtained. This is rarely tried on a ship, but in our own experience we had one notable case, a large yacht, in which the engine guides were so arranged that the screws could either revolve outwards or inwards, when steaming ahead. The owner's preference was for inward revolving screws. We tested this in the tank, and our preconceived idea that it would not be so good as revolving the same screws outwards was confirmed, and the owner consented to a double trial, with the screws reversed. As we had predicted from our tank trials, the difference in speed for the same power was fully half a knot. The following wake, with the inward revolving screws, was 11 per cent. of the ship's speed, and with the outward revolving screws, 17 per cent.

The hull efficiency	with	the	outwards	screws	showed		1·03
,, ,,	,,	,,	,, inwards	,,	,,		·95

In the ordinary type of cargo carrying vessels, the wake percentage is fairly large, but in certain other types of vessels (usually of high-speed), we have found a very small wake or none at all, and in several cases we have actually found a negative wake, with twin screws turning outwards on the top.

It will thus be seen what an extremely complicated question this interference between hull and screw is, and how essential it is that each screw should be suited to the hull which it is to drive. It is this fact which gives the screw inventor his opportunity, and he is occasionally fortunate in producing, by his patent screw, a better result than that of an ordinary but badly proportioned screw, which improvement could have been produced by altering the proportions of the screw of ordinary design.

If any one would like to study the variation in the factors that affect hull efficiency, I would refer them to Mr. Luke's I.N.A. paper of March, 1910, where the matter is dealt with at greater length.

Referring now to "cavitation" in screw propellers;—a comparatively new disease which did not affect the old sea-going engineer, and indeed does not affect the majority of marine engineers even now;—it appears in an aggravated form in high-speed vessels with small screws, and hence direct-driven turbine steamers are more likely to suffer from it, than those fitted with reciprocating engines, or geared turbines. I think it was first recognised as a special disease capable of curative treatment, by Mr. Sydney Barnaby in the *Daring*, and he cured it in that case by increasing the area of his screw blades. He was hence led to express the condition under which "cavitation" is likely to occur, in terms of pressure per square inch of projected blade area ($11\frac{1}{4}$ lbs. as a matter of fact). Since then, with screws of modern design and higher revolutions as against speed, and also turbine driven, he has found that this figure may be increased to 13 lbs. We, in our experience, have found that we have got no serious cavitation in a certain vessel with pressures up to 18 lbs. For details see Mr. Barnaby's paper read at the I.N.A. in July, 1911, and to my remarks upon his paper.

In an experimental tank such as ours, we do not reproduce "cavitation" at corresponding speeds, but the great value of such experiments is, that when the results are compared with these obtained from trials on the measured mile, we can see at what point "cavitation" begins to be serious, and at what point there is an absolute breakdown of the ship's propellers, compared with those of the model. "Cavitation" does not begin suddenly, although its worst effect (a complete breakdown) does take place somewhat suddenly.

When a screw is working in water it produces in front of it a reduced pressure. The reduced pressure causes the water to flow towards the screw. This flow is caused by the pressure of the atmosphere and water above the screw. Of course, I am not referring to the rearward flow of water towards the screw caused by the speed of advance of the ship, I am referring to the extra speed imparted to the water by the action of the screw.

Now as the atmospheric pressure is roughly equivalent to 33 ft. of water this is a more important factor than immersion of screw. This is specially so in shallow draft vessels, to which there has been a very large application of turbine propulsion. In such a shallow draft vessel the total head may be equivalent to 36 ft. of water to the centre of the screw, then the highest velocity at which the water can reach the screw is (from the formula $V_2 = 2gh$), 48 ft. per second or 2,880 per minute. Therefore one would say that until the real slip was equal to 2,880 ft. per minute, the water should follow up the screw, and there should be no cavitation. Our experiments and experience, with actual screws, show this is not nearly the truth, and that something below half this figure is quite dangerous. I do not pretend that I can give a complete explanation for this, but water is not a perfect fluid, and sea water is saturated with air and other gasses, which tend to come off and form a gas-filled cavity when the pressure in front of the screws is reduced somewhat below that of the atmosphere.

Those who desire to study more fully this question of screw efficiency—real pitch and cavitation, I would refer them to the excellent published papers of Mr. R. E. Froude, and Sir Charles Parsons, and to the books and papers published by Mr. Barnaby.

I now want to refer to some erroneous notions on screw propeller action. In the case of the disc, it will be remembered, I referred to the water thrown out to the periphery by centrifugal action, but in the case of an ordinary screw working under ordinary conditions, there is no such action, and all the inventions which have for their object the prevention of centrifugal action are quite useless. Anyone who takes the trouble to make a model screw revolve in a glass-sided tank filled with water and charged with flocculent material can easily prove the truth of this statement. Further, by fitting a spider behind the screw, to which long threads are attached, as these follow the streams of water, it will be seen that they twist, and that they show a contracted area behind the screw just as illustrated by Mr. Froude in his I.N.A. papers of 1889 and 1911.

Centrifugal action, however, can be produced by an abnormal condition. If a plate is brought up nearly touching the back of the screw, the screw changes from a propulsive instrument to a centrifugal pump, drawing the water from the driving face of the screw and throwing it out at the periphery. I have been told that in abnormal cases in which a screw has been very near to a blunt-ended barge, that when the engine was started ahead, the vessel actually went astern instead of ahead.

Just one final word of warning; we have been obliged to make many model screws at the instance of friends who had been approached by propeller inventors. It is really sad to see so much wasted energy, but it is still sadder to think that this waste will go on as before. I cannot remember a single case where we succeeded in convincing an inventor that he was wrong. He either thought that we were prejudiced, that we were not conducting the experiments properly, or that he had made some slight error which he could easily put right, and he would again approach us with some new abortion. After years of tank experiments and progressive trials on actual vessels, I should like to express my opinion that the ordinary uniformly pitched propeller of the usual shape and section of blade made of suitable pitch, diameter, and ratio of projected to disc, cannot generally be beaten by any fancy propeller. I hope that friends in future will neither waste their time, nor ours, in bringing influence to bear upon us to try still-born inventions.

I am greatly indebted to Mr. Mumford, the chief of our experimental tank, who was really responsible for the inception and carrying out of the experiments illustrated on the diagrams, and who has also prepared the experiments showing the flat sector revolving in air; also the model propeller working in water demonstrating the shape of the propeller race, and the absence of centrifugal action.*

In conclusion, I should like to say this to engineers, that the only trial which is really useful for the future study of propellers, is the progressive trial with clean bottom surface of ship, carried out on a series of runs on a proper measured mile with sufficient depth of water, and, if they are in charge of the construction of any vessel, and have the power to dictate what kind of trial shall be made, I beg of them to insist upon such progressives. The tremendous loss of valuable data which takes place every year, through the lack of these important trials is very saddening; it means slow progress towards the full comprehension of that most interesting tool, the screw propeller.

A cordial vote of thanks was accorded with acclamation to the President, on the motion of Mr. A. Boyle (Vice-President), seconded by Mr. H. A. Ruck-Keene (Member of Council). Thanks were also cordially tendered to Mr. Mumford for his assistance in pointing out the lines on the diagrams in the course of the address, and in dealing with the glass tank and accessories to illustrate some of the special points dealt with by the President.

*NOTE.—The address was illustrated by the experiments referred to, the glass tank, with propeller working by means of a motor being shown, while the action of the sector in the air was also shown by means of a fan similarly driven.

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