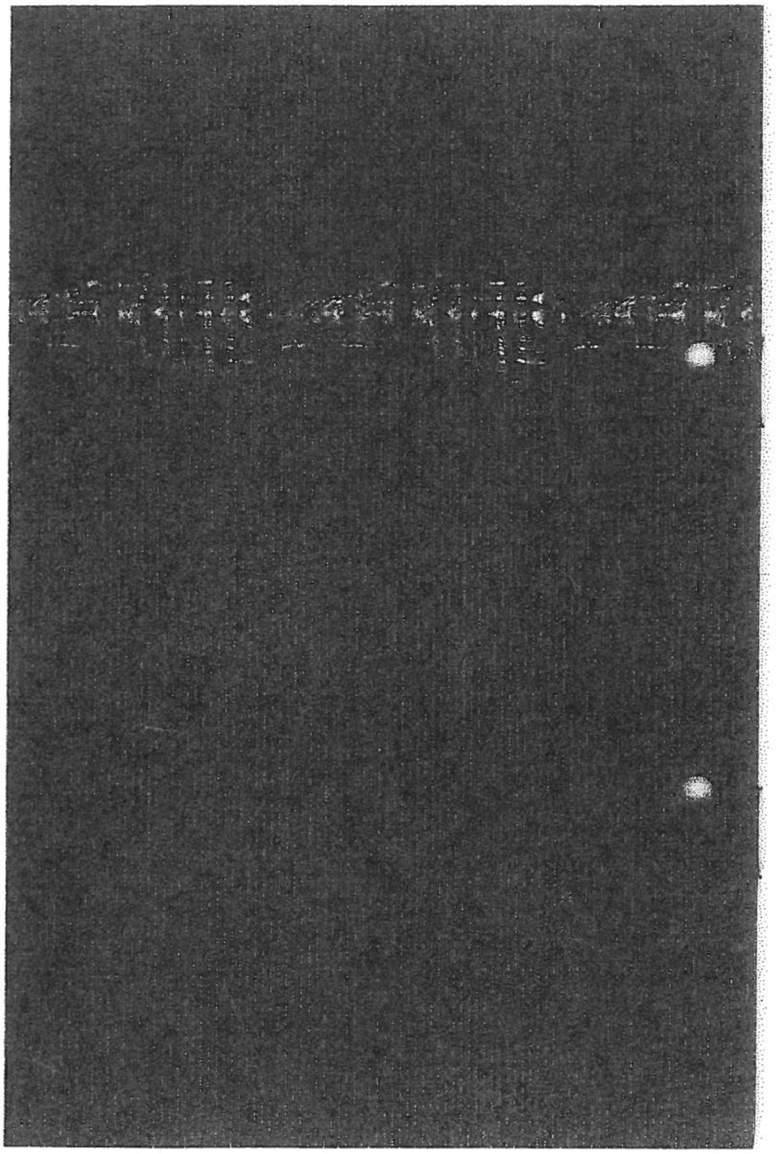

PAPERS OF THE GREENOCK PHILOSOPHICAL SOCIETY

Propeller Cavitation: The Physical Mechanism and Effects on Ship Performance

by

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being

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Propeller Cavitation: The Physical Mechanism and Effects on Ship Performance

1. **Introduction.**

The subject of my lecture this evening is the cavitation of marine propellers—the nature of the phenomenon and its effect on propeller performance. At first sight, it would appear to require the exercise of a great deal of imagination to find any connection between this subject and the work of that great engineer and inventor James Watt in whose honour this meeting is held, as he could have had no idea of the possible use of the latent power of steam for the propulsion of ships through the medium of the screw propeller.

On the other hand, I feel certain that the phenomenon of cavitation would have been of the greatest interest to him—as it was to that other great pioneer of steam engineering, Sir Charles Parsons—had he been confronted with it.

The reason for this is that cavitation is caused by the ability of water to change its state and assume the form of vapour (or steam) not only when its temperature is raised under ordinary conditions of pressure, but also when the ambient pressure is reduced under ordinary conditions of temperature.

2. **Action of Propeller.**

A marine screw-propeller is essentially a jet-propulsion mechanism which derives its motive effect by exercising a suction on the water which lies ahead of it, drawing it in to itself and then discharging it aft in a well-defined thrust column or slip-stream, as shown in Fig. 1. Immediately behind the propeller the pressure of the fluid is augmented by the action of the rotating blades and this augment of pressure at the disc is then translated into a change of velocity of the mass of water in the slipstream, as the pressure returns to the normal pressure of the surrounding fluid. It is the change of momentum of this mass of fluid, on which the propeller works in unit time, which by virtue of Newton's Second Law provides the thrust (or propulsive force) of the propeller.

The blades of the propeller are set at an angle to the direction of motion and the effect of the flow past the blades, once a steady flow regime has been established, is to cause a positive pressure on the driving face and a reduced pressure (or suction) on the back. The sum total of these forces corresponds to the pressure-reaction of the blades relative to the water, which may then be resolved in the axial and rotational directions to give the thrust and torque forces. It so happens that under normal working conditions this suction force—if I may be permitted to use such a term—exceeds the pressure force by about four times, so that it will be seen that the working of the propeller is attended by the creation of regions of intense suction on the blades, particularly if the thrust required is large.

For example, if a propeller is absorbing, say, 20,000 horse-power and advancing at a speed of 20 knots then the total thrust will be just over 100 tons, and about 80 tons of this will be provided by the suction on the back of the blades.

3. Physical nature of cavitation.

If the local pressure at any point on the blades, or at any point in the fluid falls below the vapour pressure, a cavity will be formed filled with water vapour and some occluded air, since air is always present in sea water. These cavities may exist in several different forms, and Figs. 2 to 7 illustrate the general appearance of cavitation as seen on the model propellers in the Cavitation Tunnel at Newcastle. Firstly, there is **sheet cavitation** (see Fig. 2), in which considerable areas of the blade appear to be completely denuded of water, secondly, there is **bubble cavitation** (see Fig. 3), in which large individual bubbles are formed and can be seen to expand and then collapse, and in the third place there is **cloud cavitation** which has the appearance of a fine mist and seemingly takes the form of a multitude of minute bubbles.

The terminal vortices which stream away from the tips of the blades may also cavitate under certain conditions, as shown in Figs. 4 and 5. These tip-vortices are similar to those which occur at the ends of an aeroplane wing in flight, and which are sometimes made visible in the sky, in the form of vapour trails. Fig. 6 shows the existence of a central vortex-core in addition to the tip-vortices. This can only be seen when the Tunnel is run in the opposite direction and there is no shaft behind the working screw.

Finally, Fig. 7 shows the appearance of the cavitation when complete breakdown occurs. All these forms are essentially

boiling phenomena, and it can therefore be said that the action of the propeller blades causes the surrounding water to boil under ordinary temperatures.

Now this, of itself, may be regarded as only another interesting natural phenomenon, and one which is fascinating for the physicist to contemplate. It could well have happened that its effects on the performance of a propeller might have been negligible, but unfortunately this is not so.

In the first place, when the cavitation sheet—which usually starts at the tips and spreads down the blades—has extended to about .75 of the radius it is found that there is a considerable loss in thrust, followed by a diminution in torque, which means in practice that there will be a marked increase in revolutions for a given engine power. Since the thrust breakdown proceeds more rapidly than the change in torque there is also a very considerable loss in efficiency. In the second place, the cavitation bubbles when formed cannot persist if they are swept into a region where the pressure returns to a value exceeding the vapour pressure of the water, and the manner in which they collapse introduces a new phenomenon. The now classical work of Parsons & Cook showed that the bubbles do not explode, but implode. That is to say, the bubbles contract to a very minute size before they disappear and the whole of the energy of collapse and change of state is therefore concentrated on a very small area indeed. This phenomenon is very closely related to that known as "water-hammer," and the two authors mentioned showed, experimentally, and by calculation, that the final pressure at the point of collapse may exceed 20,000 atmospheres (or 150 tons/sq. in.). This has a most disastrous effect on the surface of the metal of the blades, which is quickly eroded if the cavitation persists for any length of time.

4. Mechanical effects of cavitation.

In the initial stages of the attack the metal takes the appearance of having been struck rapidly with a small "peening" hammer, minute circular indentations are seen on the surface marking the point of collapse of successive bubbles and the surface of the metal is stretched. This is evident from the fact that the first effect of cavitation near the trailing edge of a blade, on the back, is to cause a curling of the edge towards the face. This is not an uncommon experience in merchant ship propellers, when incipient cavitation is present in the outer parts of a propeller blade, and its effect on the performance of the propeller is rather peculiar.

The curling of the edge towards the face is similar to the turning down of the ailerons on an aeroplane wing. The lift of the section is markedly increased and the resulting increase in torque causes the revolutions of the main engine to be reduced for the same engine setting. I have, for example, known two or three instances in which the trailing edge, at about .8 radius, has been turned down by about 1" over a length of some 9" to 12", on each blade, and this has resulted in a diminution of about 8-10 revolutions per minute. When the edge has been straightened the revolutions have returned to the normal value, but a few further months in service have again resulted in the edges curling in precisely the same manner, with the same disastrous result on the revolutions and consequently on the mean effective pressure in the cylinders of the engine. Finally, the offending portion of the blade was cut off and although the cavitation may have increased, the collapse of the bubbles now occurred outside the edge of the blade and the revolutions remained at the desired level. That the curling of the edge of the blade was due to the mechanical impact of the collapsing bubbles is to my mind amply demonstrated by the fact that the same effect can be produced by allowing a pneumatic hammer to play on the back of the blade, and this mechanical "peening" effect has in fact been used in practice to alter the effective-pitch of a propeller, or to straighten a damaged blade. This is a very curious instance in which the working of a machine causes it to deflect in such a manner as to increase the load which it carries; usually the opposite is the case

If the cavitation is more extensive, or persists for a longer time, then it results in serious pitting or erosion of the metal. It is believed that this is due to the metal near the surface being work-hardened and then torn away by the action of the impacting bubbles, thus causing a definite crater, or a series of craters, in the surface of the blade. The cavitation in the affected region is then increased and pieces of the metal are torn out leaving the sponge-like appearance which is characteristic of advanced cavitation erosion. In some instances the pitting continues until the whole of the thickness of the blade is eaten away, and finally there may be a hole completely through the blade from back to face. The photograph reproduced in Fig. 8 shows one instance where the whole of the tip of a blade was eaten away and then torn off completely by this action. This was a cast-iron propeller turning at only about 65 revolutions per minute and the damage shown took place in about 6 months normal service. Fig. 9 shows the propeller of a large Atlantic-liner in which large craters were formed in the driving face of the blades near the leading edge. Erosion due to cavitation may occur at any part of a propeller blade where the suction is high, but it most usually occurs at

three significant parts, namely, at the tip where the rotational velocity is highest, at the .7 radius where the load is usually at a maximum and towards the root of the blades where the sections are of necessity very thick and the pressure distribution is adversely affected by the small gap between the blades. In wide-bladed destroyer and M.T.B. propellers it also frequently occurs in the fillets or on the surface of the boss itself; although this is obviously only a particular example of the latter type, where the cavitation plume is entrained towards the surface of the boss or cone. I have, for example, seen cavities 7" deep near the fillets of a large liner propeller after only a short period in service, in addition to the blades being completely penetrated through a thickness of metal of about 2¼" at the .75 radius. The designer must therefore pay particular attention to the flow round the sections in the three regions mentioned, and estimate the suctions which are likely to occur in normal service.

5. Vibration and noise effects.

In addition to the losses in thrust and efficiency and the erosion troubles which have been mentioned, advanced cavitation also introduces extremely unpleasant vibration and noise phenomena. The collapsing cavities give rise to a loud crackling and buffeting noise, and the sound of a cavitating propeller has frequently been likened to the sound of a hailstorm or to the noise of a pneumatic riveter beating on the hull. This noise is accompanied by intense vibrations of a high frequency, which can be extremely unpleasant to passengers and crew.

The question as to whether the "singing" of propellers is due to cavitation has not been completely resolved.

The fact that propellers which cavitate badly do not "sing" has frequently been observed, and this has tended to confuse the issue, but recent tests made in the cavitation tunnel at Newcastle have indicated that "singing" occurs just before the terminal vortex is clearly formed when there is a tiny bead of cavitation on the leading edge of the back near the tip, or alternatively when there is a very slight fringe on the face about half-way down the blade just near the leading edge. The note emitted appears to vary with the position of this tiny bubble on the blade, suggesting that different natural modes of vibration may be excited in this way.

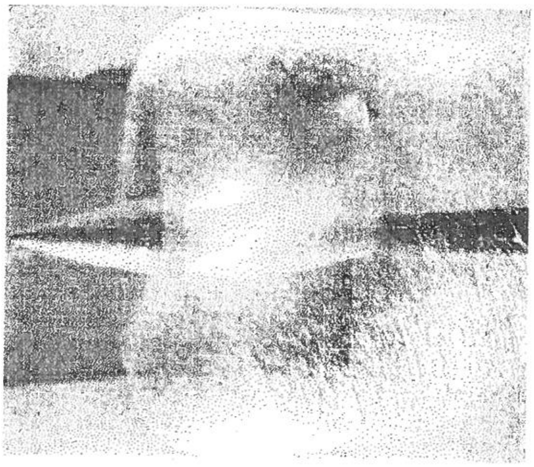
Much further study is required before the phenomenon of "singing" can be completely explained, but on information available and particularly in the light of these tests, I would venture to suggest that when "singing" is present there will probably be a small bubble of cavitation somewhere on the blades, and preferably near the edge, which is literally "dancing" on the blade like a bead of water on a hot surface. In other words, there is a very close connection between the "singing" of a propeller blade and the "singing" of a kettle which is just about to boil; the phenomenon which, according to tradition, first attracted the attention of James Watt to the peculiar properties of steam. Of course, the blade will be in vibration in some particular mode or combination of modes of vibration and eddies will be shed from the trailing edge in a regular fashion as will be seen in Fig. 10. The periodic shedding of these eddies will undoubtedly affect the circulation round the blade section and it is not difficult to imagine the sequence of events whereby the periodicity of eddy-shedding, the response of the blades, and the incidence of the incipient cavitation on a suitable point of the blade all play their part in determining whether the "singing" will be continuous or intermittent, loud or barely audible.

6. **Early experiences of cavitation phenomena.**

Having described some of the effects of cavitation, I think I should now review very briefly the history of our knowledge of this phenomenon and describe how our present ideas concerning its action and the means whereby it can be avoided have been developed.

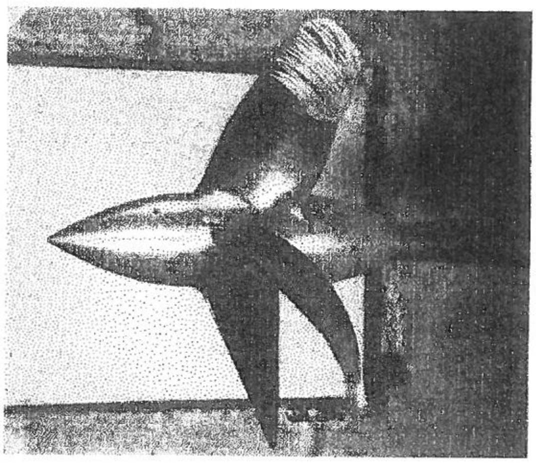
It appears that this phenomenon first attracted the attention of engineers and shipbuilders in connection with the small fast-running propellers of the high speed torpedo-boats which were developed during the final decade of last century. There was, for example, the case of the "Daring" where the speed obtained on trial in 1894 was only 24 knots for the full power of 3,700 I.H.P. at 384 r.p.m. and which finally achieved a speed of 27 knots at 373 r.p.m. with the sixth propeller tried, the significant difference being an increase in blade area from 8.9 sq. ft. to 12.9 sq. ft. There was also the almost simultaneous experience of the Hon. Sir Charles Parsons with the "Turbinia," which at first only obtained a speed of $19\frac{3}{4}$ knots at 1,780 r.p.m. with a slip of 37.5 per cent, and finally achieved the speed of $32\frac{3}{4}$ knots with nine propellers arranged on three shafts at a reported equivalent I.H.P. of 2,000 and with revolutions of 2,300 on the wing shafts and 2,000 on the centre shaft. This multiple propeller arrangement was used by Parsons on a number of ships, in order to increase the amount of blade area, but it was later abandoned.

In a letter dated 3rd April, 1895, Parsons quotes Froude as being the first to name the phenomenon "cavitation," although



Direction of advance

Fig. 1 PROPELLER SLIPSTREAM



Direction of advance

Fig. 3 SHEET CAVITATION

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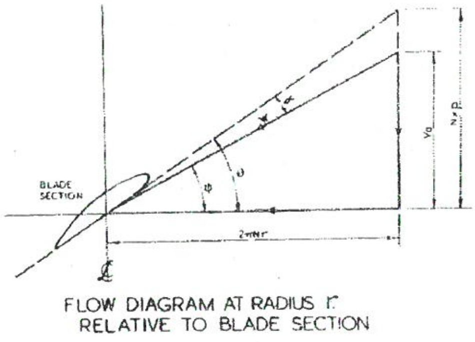


Fig. 16 FLOW DIAGRAM AT RADIUS r.

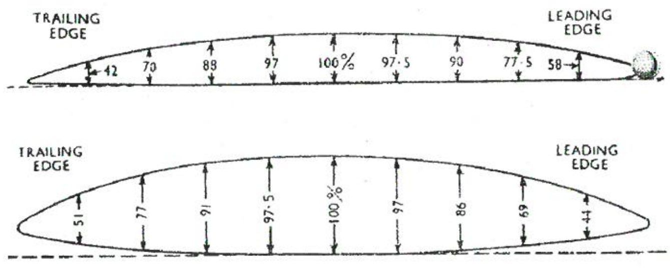


Fig. 17 UNIFORM-VELOCITY TYPE SECTIONS

it appears to have been S. W. Barnaby, author of the 1906 James Watt Anniversary Lecture, who first explained the effect of blade area and gave the criterion of a limiting thrust per sq. in. of projected area of 11¼ lbs. for its avoidance. These early experiences of extreme cavitation due to high speeds of rotation appear to have been eliminated mainly by the introduction of high-speed reduction gearing in 1897—this was an experimental installation which when opened up in 1904 was found to be in perfect order. The first destroyer with reduction gearing on both shafts was the "Leonides," built in 1912.

As the horsepower of the various installations continued to rise, the effects of cavitation began to be manifested in another form, namely, erosion and pitting of the blades, due to the high thrust loading.

In 1895, Parsons made the first small cavitation tunnel, which is still in existence in Newcastle, and although this has been described before, I feel this lecture would be incomplete without a picture of this tunnel (see Fig. 11), in which 2" propellers were tested and the nature of the phenomenon was first revealed. In 1910, Parsons built the first large cavitation tunnel at Wallsend in which model propellers 12" in diameter were tested (see Fig. 12), and this continued in operation up to the time of his death in 1931, although, unfortunately, the information gleaned from his tests remained confidential to his Company, and the full extent of his work on this subject was not revealed until published in the 1950 Parsons Memorial Lecture.

In the intervening period, cavitation troubles were encountered in various forms, mainly on high-powered ships. For example, the early propellers of the large liners, which were built before the first world war suffered from extreme face-cavitation and erosion, which could have been avoided if the full nature of the phenomenon had been known. The propellers of several of the large super liners built in the early post war period had deep erosion near the root sections, and I suspect that it was this which led to the erection of the Hamburg Tunnel which was commenced in 1928 and completed in 1931. This was quickly followed by the erection, within the period of the next ten years, of a number of other tunnels in different countries, and notably in the United States (1931), in Great Britain (1932), and in Holland (1938). There are now ten such tunnels in which propeller cavitation tests may be made, the latest to go into operation being the large tunnel at King's College, Durham University, Newcastle-on-Tyne, which was completed in 1949.

7. The Durham University Tunnel.

This tunnel, which is 40′ long by 35′ high, forms an approximately rectangular closed circuit as shown in Fig. 13. The impeller, which can circulate the water in either direction, is placed in the lower horizontal limb, and the measuring section, in which the model propeller drive is arranged, forms part of the upper horizontal limb. The measuring section is 40″ deep by 32″ wide by 12′ long, and it is generously provided with windows for viewing and photographing the model propellers, as shown in the photograph reproduced in Fig. 14. The stroboscopic lighting equipment provides a single, short duration, high intensity flash once per revolution with the propeller in precisely the same position each time. Under this lighting the propeller appears to be stationary and the growth of cavitation and other transient phenomena may be observed. A single ultra-short, high intensity flash is also provided which enables single photographs of high resolution to be taken. The flash lasts for one microsecond and has an energy of 500 joules. In order to take ciné-film records of the progress of phenomena in the cavitation tunnel an additional lighting system has been developed giving 16-joule flashes of 5 microsecond duration at precisely the same propeller position every time a frame arrives in the ciné-camera gate. The total head at the centre of the measuring section may be varied at will by altering the pressure in the small vacuum chamber at the upper left-hand corner in which there a free surface. Thrust and torque measuring gear are provided on the model propeller drive that enters the upper limb of the tunnel from the right-hand end, which is divided for this purpose.

These arrangements are more or less common to all cavitation tunnels, and in order to illustrate the manner in which such a tunnel works, and at the same time to exemplify, in what is I believe the best possible way, the modern approach to the study of cavitation in marine propellers, I propose to show a short film, lasting about 15 minutes, which will clearly demonstrate the changing picture of the cavitation on the blades of a 16″ model propeller, as the conditions of running are altered.

In the first sequence the general features of the tunnel and the model propellers which are tested, will be seen. This will be followed by an actual test on a four-bladed propeller, such as would be fitted to a high-speed cargo liner, in which the water speed is maintained constant and the revolutions are increased. In this way, it will be possible to see first of all the cavitation on the face corresponding to a very low or negative slip angle, followed by the emergence of the terminal vortices and the appearance of cavitation on the back of the blades. As the

revolutions increase, sheet cavitation spreads down the blade, accompanied by bubble cavitation on the inner parts, until finally the whole of the back is covered with cavitation. The water speed and revolutions will then be maintained constant and the head varied.

8. Modern approach to cavitation problems.

Since S. W. Barnaby first proposed a limiting thrust per square inch of blade surface as a suitable criterion for the avoidance of cavitation our knowledge of the action of a marine propeller has increased very considerably and this has led to a different approach to the problem. Admiral D. W. Taylor in 1909 carried out a number of tests in open water with propellers specially designed to cavitate and he then proposed a limiting tip speed of 12,000 feet per minute (or 200 feet/sec.). Several other investigators since that time, and notably Irish in 1929 have suggested the combination of a suitable limiting thrust per square inch and a limiting tip speed. Such global criteria do not, however, allow much scope for variations in design and modern considerations are based mainly on the lift-coefficients at which the several sections of a propeller blade will be working in service, judged in relation to a cavitation number $\sigma=p-e/q$, where "p" is the static pressure due to (water head + atmospheric head), "e" is the appropriate vapour pressure and "q" is the dynamic pressure $\frac{1}{2}\rho V^2$ arising from the stream velocity V.

In order to explain this procedure in simple terms, it is necessary first of all to state that a propeller blade acts precisely in the same manner as an aeroplane wing in flight. If this can be accepted, then we can consider first of all what would happen if a simple aerofoil (or aeroplane wing) were to be towed under water at different speeds of advance. The pressure distribution around such an aerofoil would depend upon (a) its cross-sectional shape and (b) its angle of incidence relative to the line of advance. Fig. 15 shows, for example, the pressure distribution around two alternative forms of sections at a small positive angle of incidence. So long as the angle of incidence remains constant the shape of the pressure distribution curve will remain the same: it is usually plotted in relation to the stagnation pressure $\frac{1}{2}\rho V^2$ at the nose (i.e. at the point where the face and back stream divide). If, therefore, the speed of advance is doubled then the maximum suction will be increased four times, if it is trebled then the suction will be increased nine times, and so on. It will thus be obvious that as the speed is increased the back-suction peak increases rapidly and will soon reach a point when the local pressure falls to the level of the vapour pressure. When this occurs, any further increase in suction will cause a sudden rupture of the water surface in contact with the section and a bubble or cavity will be formed.

As the flow is continuous this bubble will be entrained with the fluid and thus enter a region where the pressure is increasing, and Professor G. Knapp, of the California Institute of Technology, and others, have shown by means of extremely high speed ciné-photography that each bubble collapses, reappears by a kind of "rebound" phenomenon, collapses again, and then reappears several times before it finally disappears.

From the two pressure-distribution diagrams I have shown, namely, for a round-back section and an aerofoil section, respectively, it will be obvious that the maximum suction on the latter exceeds that on the former; so that cavitation will occur at a lower speed of advance with the aerofoil section than with the corresponding round-back section.

In fact, the total area under the pressure curve, including both the sub-pressure on the back and over-pressure on the face, represents for all practical purposes the lifting force acting on the section, or, if these are plotted in relation to the stagnation pressure and the chord is taken as unity, it represents the lift coefficient, where

$$C_L = \text{lift coefficient} = \frac{\text{lifting force}}{\frac{1}{2}\rho A V^2} \quad (\text{where } A = 1.0 \text{ in this case})$$

and as the maximum suction may also be expressed as

$$\frac{\Delta P_{max}}{\frac{1}{2}\rho V^2} = \text{max. suction coefficient,}$$

we have, approximately, for the round-back section

$$\frac{\Delta P_{max}}{\frac{1}{2}\rho V^2} = 1.20\ C_L$$

and for the aerofoil section

$$\frac{\Delta P_{max}}{\frac{1}{2}\rho V^2} = 1.46\ C_L$$

and furthermore, since cavitation occurs when

$$\Delta P_{max} = (p-e)$$

we can see that cavitation will occur with the round-back section when

$$\sigma = \frac{p-e}{q} = 1.20\ C_L$$

and for the aerofoil section when

$$\sigma\ \text{aero} = 1.46\ C_L$$

In other words, for a given value the permissible lift-coefficient is given by

$$\text{permissible } C_L = \frac{\sigma}{1.20} \quad (\text{round back section}).$$

and

$$\text{permissible } C_L = \frac{\sigma}{1.46} \quad (\text{aerofoil section}).$$

If, for example, the lifting plane (or wing) was travelling at a distance of 10 feet below the water surface at a speed of 100 feet per sec., the atmospheric pressure would be, say, 14.7 lbs./sq. in., the water head 4.5 lbs/sq. in. and the vapour pressure .26 lbs./sq. in., so that

$$(p-e) = 14.7 + 4.5 - .26 = 18.92 \text{ lbs./sq. in.}$$

$$\text{and } \tfrac{1}{2}\rho V^2 = \tfrac{1}{2} \times \frac{64}{32.3} \times \frac{100^2}{144} = 69 \text{ lbs./sq. in.}$$

or

$$\sigma = \frac{18.92}{69} = .274$$

and under these conditions cavitation would occur at a lift coefficient of

$$C_L = \frac{.274}{1.48} = .188 \text{ for an aerofoil section.}$$

or

$$C_L = \frac{.274}{1.20} = .228 \text{ for a round-back section.}$$

Alternatively, if the lift-coefficient was .20 for each type of section then the aerofoil section would cavitate at 96 f.p.s. and the round-back section at 106.8 f.p.s.

Now let us compare this with the section of a propeller blade situated at a radius of 9 feet and rotating at 100 r.p.m., with a speed of advance of 12 knots. In this case, we have

$$\text{rotational speed} = 2 \times 9 \times \frac{100}{60} = 94.2 \text{ fps.}$$

$$\text{advance speed} = 12 \times 1.689 = 20.25 \text{ fps.}$$

$$\text{and the resultant speed} = \sqrt{8874 + 410} = 96.3 \text{ fps.}$$

so that for a lift coefficient of .20 the aerofoil section would be just on the point of cavitating whereas the round-back section would have a margin of about 10 r.p.m. before this occurred.

This is a very simple example, but it illustrates the manner in which a modern non-cavitating propeller may be designed. In practice, the resultant velocity at each radius relative to the blade section is found by combining the axial velocity and the rotational velocity as above (see Fig. 16) and then making an additional allowance for the inflow velocities caused by the action of the propeller itself. The blade section must then act at a small angle of incidence to this final resultant velocity, at each radius. This accounts for the pitch angle of the blades, and the designer by choosing the diameter and pitch for a given application automatically fixes the angle of incidence at which each section will work in service. If, for example, he chooses a small diameter and a high pitch for a given job the angles of incidence will be greater than if he chooses a large diameter and a small pitch, although the power absorbed and the speed of rotation may be the same in each case. From the simple considerations outlined above it will be obvious that in order to avoid back cavitation it is advisable to adopt a low angle of incidence where possible, in order to reduce the working lift-coefficient, but there is a practical limit to this procedure, because when the incidence is reduced beyond a certain point the shape of the pressure distribution diagram changes and important suction peaks occur on the face near the leading edge; consequently there is danger of face cavitation. So far as the thick root sections are concerned, these can usually carry a higher suction than the thinner outer sections because of the increased head of water available, and furthermore the danger of face cavitation occurs at a higher angle of incidence as the thickness is increased. For these reasons, it is usual to arrange for the inner blade sections to work at a higher lift-coefficient than those in the outer parts. For example, while the lift-coefficient may be only .10 for the sections near the tip, the lift-coefficient of the inner sections may be as high as .60. When the propeller is working behind a ship, it so happens that the axial speed of the water near the boss is considerably reduced by the wake-concentration which occurs in this region. This automatically increases the angles of incidence towards the root of the blades, so that, even allowing for an increased lift-coefficient for these sections, it is usual to adopt a pitch-reduction towards the root of the blades.

Finally, it should be mentioned that a given lift-coefficient may be obtained either by giving the sections a small centreline camber and a relatively large angle of incidence, or vice versa, and that there is an optimum centreline camber for each lift-coefficient, which places the stagnation point exactly on the nose. It is also possible to vary the shape of the contour of the blade sections so as to obtain an almost uniform suction on the back. See, for example, Fig. 17 which shows two typical blade sections for use in the outer and inner parts of the propeller blade respectively. The thicker section gives a back suction distribution which increases slightly towards the trailing edge for small angles of incidence, while the thinner outer section gives a more or less uniform suction on the back.

9. Recent experience, and means of avoiding cavitation.

In recent years, owing to the increased speeds of merchant ships, which have been achieved mainly by the adoption of higher powers and higher revolutions per minute, it has become increasingly difficult to avoid the effects of cavitation.

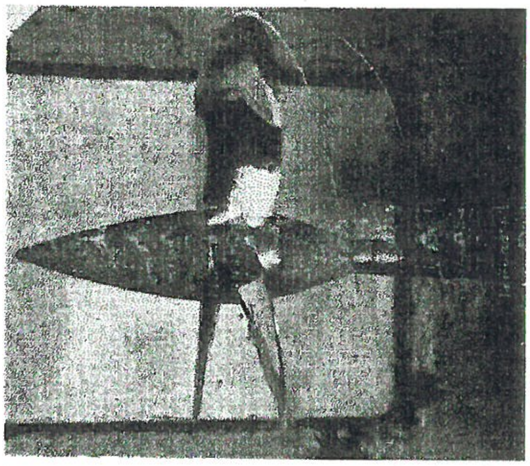
This is particularly so in the case of high speed cargo-liners where the increased powers have been transmitted on a single shaft, because in the single-screw arrangement and with a relatively full after body the propeller is working in an extremely high and variable wake; consequently the angles of incidence at which the blade sections are working alter very considerably during the course of each revolution.

For example, it is possible for each propeller blade to be quite free from cavitation in the outboard position (i.e., when at right-angles to the vertical centreline of the ship) where the velocities are relatively high and then to cavitate on the back when passing through the upper part of the aperture, where, owing to a frictional wake belt, the axial velocities are low.

Alternatively, if the propeller blade tips are free from back cavitation when passing through the aperture, they may suffer from face cavitation during the remainder of the revolution.

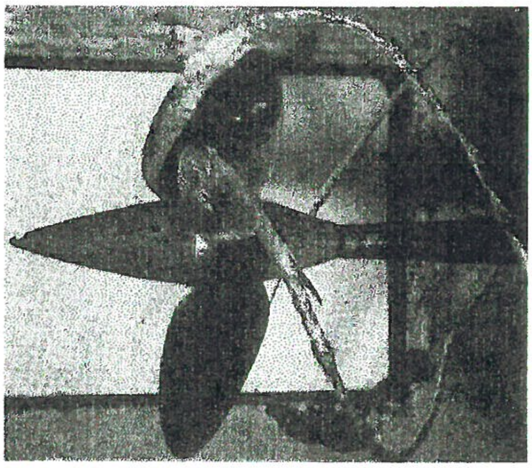
The means whereby the designer can meet the challenge of higher revolutions and ever increasing loading are as follows:—

1. To increase the amount of blade area and thus reduce the thrust/sq. in. of surface.
2. To diminish the blade angles and angles of incidence by adopting slightly larger diameters.
3. To adopt different pitches at different radii of the propeller in order to diminish the loading in critical regions.



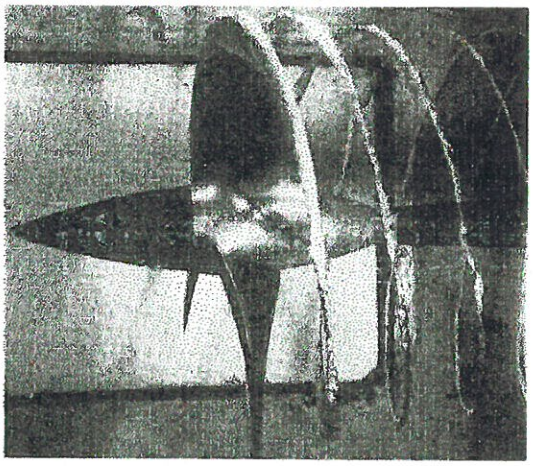
Direction of advance

Fig. 3 BUBBLE CAVITATION



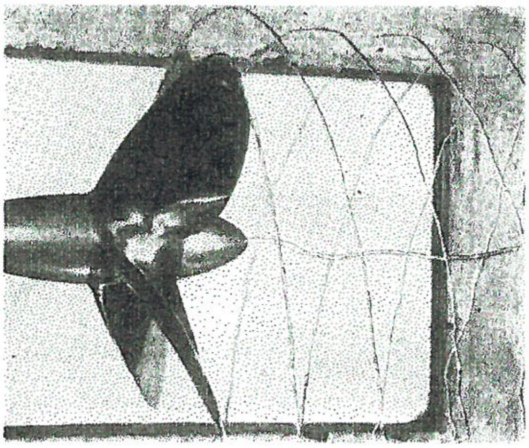
Direction of advance

Fig. 4 TIP-VORTICES (HIGH PITCH ANGLE)



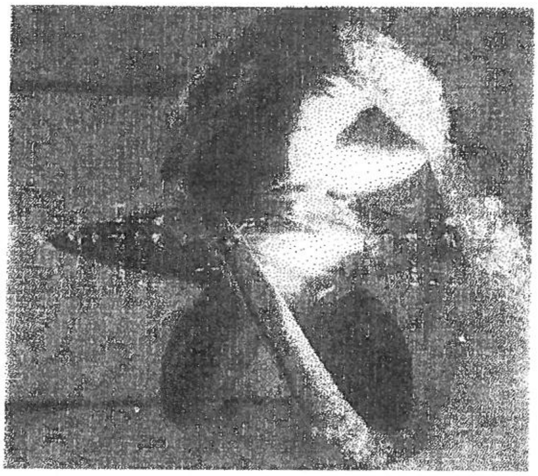
Direction of advance

Fig. 5 TIP-VORTICES (LOW PITCH ANGLE)



Direction of advance

Fig. 6 APPEARANCE OF CENTRAL VORTEX-CORE



Direction of advance

Fig. 7 COMPLETE BACK CAVITATION

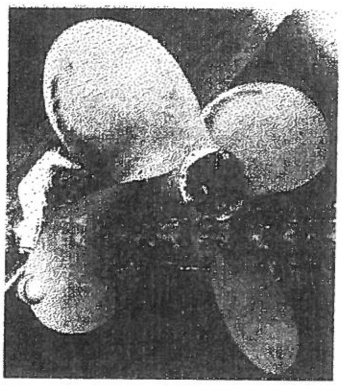


Fig. 9 DEEP FACE EROSION

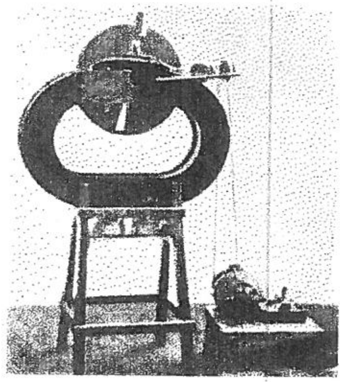


Fig. 11 THE FIRST CAVITATION TUNNEL (1895)

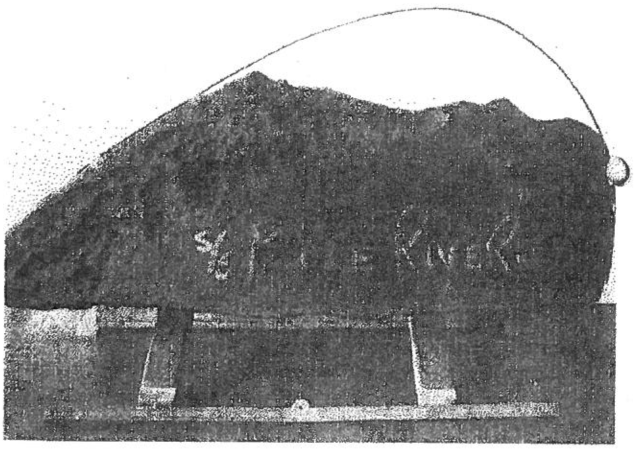


Fig. 8 EROSION AT TIP OF BLADE

Fig. 10 PROPELLER "SINGING" IN TUNNEL

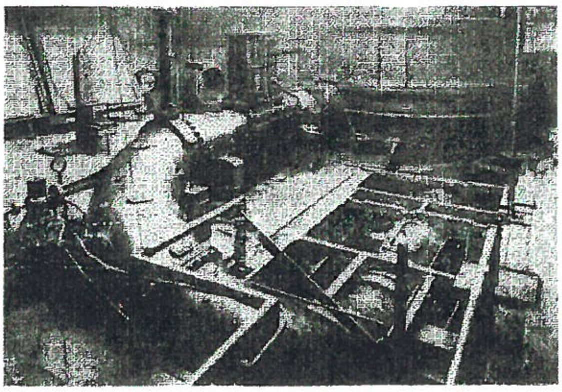


Fig. 12—PARSON'S LARGE CAVITATION TUNNEL (1910)

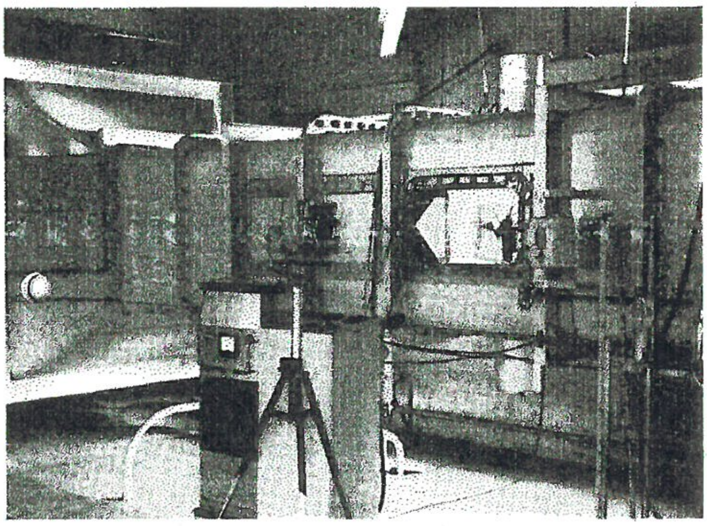


Fig. 14 MEASURING SECTION OF TUNNEL

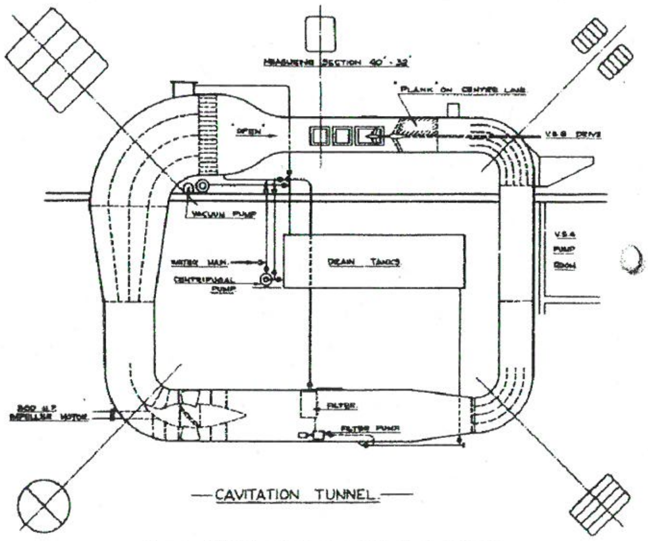


Fig. 13 KING'S COLLEGE CAVITATION TUNNEL

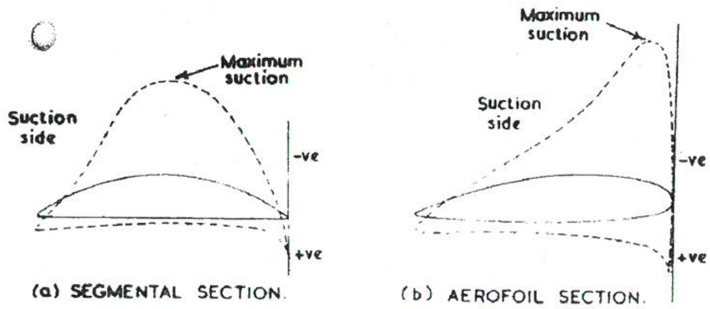


Fig. 15 PRESSURE DISTRIBUTION ON TYPICAL BLADE-SECTIONS

4. To avoid the occurrence of unduly high suctions on the back of the blades by using section shapes which give a more uniform distribution of pressure.

5. To avoid the incidence of local suction peaks near the leading edge by using suitable amounts of centreline camber and a suitable shape of entrance.

6. To reduce the thickness of the blades.

10. New materials for propellers.

The last item in the above table is related to the possibility of using new materials which are stronger and more resistant to the effects of cavitation. Briefly, there is no metal, including the hardest steels, which is completely resistant to the destructive action of cavitation, but recent work in the metallurgical field has led to the development of several new alloys, such as the nickel-aluminium bronze alloy which gives a breaking strength of 42 tons/sq. in., as compared with about 32 tons/sq. in. for normal maganese bronze, and about 18 tons/sq. in. for cast iron, and which at the same time has a very much increased resistance to both erosion and corrosion. This makes possible the use of thinner blade sections and thus extends the range of thrust-loading which can be accepted by the designer without risk of erosion damage to the blades.

The problem of avoiding cavitation is still essentially a question of design, but if the metallurgist can resolve the physical and chemical problems of the erosive action of the collapsing bubbles and produce still further new materials which can sustain the severe blows without serious deterioration of the surface, this will most surely lead the way to further advances in propeller performance and ship speeds.

11. Conclusion.

In conclusion, I should like to say that I appreciate very greatly indeed the honour and privilege of presenting this Anniversary Lecture in memory of that great engineer and scientist, James Watt. I can only express the hope that, although factual rather than philosophical, it has—in one way or another—been worthy of your great tradition.