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THE HARMFUL EFFECTS OF CAVITATION ON MARINE PROPELLERS.

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SYNOPSIS.

The three troublesome effects that propeller cavitation can have on ship performance are :

(1) loss of thrust

(2) erosion of the propeller blades

and (3) noise and vibration

These effects have emerged in the above order, and each has assumed importance at different times as ship forms have changed and engine powers have increased.

It has been necessary to develop an understanding of the cavitation problem and its effects in order to devise and apply corrective action. Theoretical approaches have in general been found inadequate at the time action has been required, and it has been necessary to resort to model experiments to develop knowledge of each aspect of the subject. This has led to interesting theory/model/full scale correlation.

The first two of the harmful effects listed can now be avoided with reasonable success by the propeller designer. The third is still under investigation, and it appears that more attention should be paid to hull design in order to avoid continuing troubles.

This lecture briefly covers the historical background to the problems, the steps taken to overcome these, and some experiences from actual full scale operation.

INTRODUCTION

Among the many varied, and sometimes conflicting, requirements which have to be met by the marine propeller designer is one which often states that the propeller shall be free from cavitation. It is now generally accepted that in the environment in which screw propellers must operate this requirement is impossible to achieve, and it is, therefore, modified to read "free from the harmful effects of cavitation". These effects in themselves vary considerably, and each has assumed a different degree of importance as ship types have developed over the years. The earliest problems with propeller cavitation concerned loss of thrust. As shaft powers increased problems of cavitation erosion of the blade surfaces were encountered. More recently it has been appreciated that the forces giving rise to noise and ship vibration are increased many times in magnitude when propeller cavitation occurs.

Over the period of eighty years dating from the end of the nineteenth century practical and theoretical investigations have been going on continuously in many parts of the world, initially to understand the physical mechanism of the cavitation phenomenon, and later to endeavour to predict the likely presence and effect of cavitation in conjunction with any particular ship form.

The latter task, on a theoretical basis, is formidable since it requires a detailed knowledge of the velocity distribution through the propeller disc, the performance characteristics of the propeller at each point during the revolution, and the corresponding pressure distributions around the propeller blade sections at each radius.

These data form the basis of a quasi-steady consideration of the problem - at present there is no non-steady theory available which will take account of the transitional conditions as the propeller blades pass from one wake region to another. These quasi-steady calculation results have been compared with model and full scale results and have given good hopes of success in subsequent prediction work.

Model testing techniques in conventional tunnels have improved to the point where it has in many cases become possible with reasonable certainty to predict whether propeller blade erosion will take place on full scale.

Considering propeller excited, or cavitation excited, vibration, theoretical approaches to prediction are inadequate at this stage. New methods of testing have been devised in which the propeller can be run behind a full model of the actual ship for which it was designed, at the correct cavitation conditions, so that pressure measurements can be made for comparison with full scale results.

EARLY HISTORY

The effects of propeller cavitation were first experienced by Barnaby and Thornycroft in their trials of the warship "DARING", when it was found that above a certain power no further increase in ship speed was possible, while the shaft revolutions continued to increase rapidly. Soon after this. Sir Charles Parsons experienced the same problem during the trials of the experimental steam turbine ship "TURBINIA".

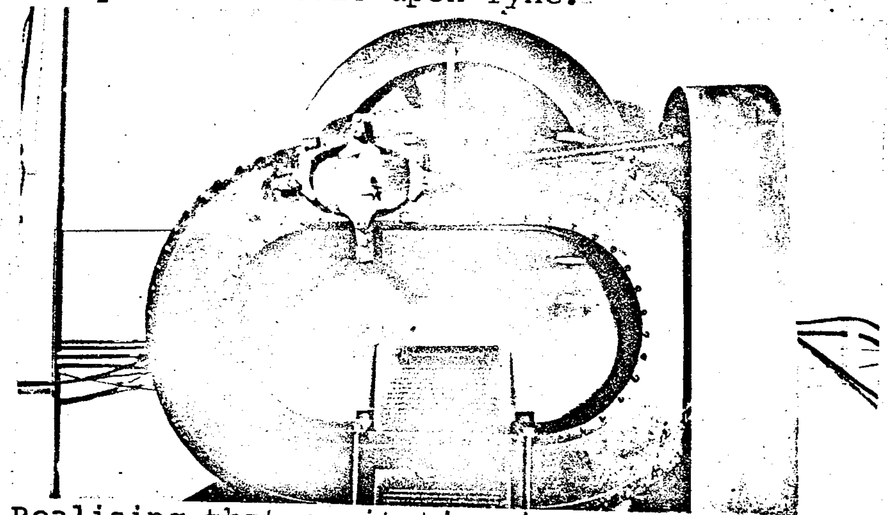
Barnaby and Thornycroft overcame the problem by experimenting at full scale, and discovered that an improvement was achieved by an increase in blade surface area. Parsons also experimented at full scale, and made some important discoveries which we today accept as normal.

These included the realisation that it was impossible to absorb a high power on a single screw at high r.p.m. TURBINIA originally had a single screw, but Parsons, finding that this propeller was unable to produce the required thrust, adopted a triple screw arrangement, and in fact, used three screws on each shaft, nine in all. These were, as a matter of interest, 18 inches in diameter and 24 inches in pitch, each with a blade area ratio of about 0.60. The total power absorbed was about 2300 SHP with trial r.p.m. of 2230 on the outside shafts and 2000 on the centre shaft, giving the ship a speed of 32¾ knots.

In order to understand the reasons for the success of these decisions, Parsons embarked on a series of model experiments to investigate the nature of cavitation. These initially consisted of rotating a small model propeller in an open bath, heating the water to a little below boiling point to stimulate the onset of cavitation. Later he designed and made a small closed copper circulating channel which was the forerunner of cavitation tunnels as we know them today.

The original Parsons' tunnel is still in existence, and is in the care of the Naval Architecture Laboratories at The University of Newcastle-upon-Tyne.

Fig. 1.



Realising that cavitation is not only caused when water vapour is formed by raising the temperature under normal conditions of pressure, but also when the pressure is reduced under normal conditions of temperature, Parsons reduced the atmospheric pressure above the water level by means of an air pump. This enabled the cavitation to appear earlier and make its observation possible at shaft speeds of 1500 r.p.m. instead of 12000 r.p.m. Thus the observation of the formation and collapse of the cavitation became easier.

From this early work, both model experimental and full scale, it was correctly concluded that extreme back, or suction side, cavitation of the type causing thrust breakdown could be avoided by increasing the blade surface area. Criteria were developed relating the mean thrust to the projected blade surface area in the form of a limiting unital thrust loading. A figure of about 11 lbs/in^2 was recommended, and this is consistent with the values in use on most propellers designed today.

Thus the first harmful effect of cavitation was practically solved, and has not subsequently been found to be troublesome except on some small, fast, high-revving craft of the M.T.B. type.

CAVITATION EROSION

As the powers of steam turbine machinery increased in the early part of the twentieth century, so did the shaft r.p.m. reduce with the use of gearing. Thus propellers became bigger, thrust loss was not encountered, and the other dangers of cavitation were, for some time, not appreciated. However, with further large increases in power, as on some trans-Atlantic liners, the harmful effects of cavitation took on a different form, namely that of erosion of the propeller blade surfaces.

Theoretical studies of the subject had still not reached a stage sufficiently to explain which type of cavitation may lead to erosion, and once again it was necessary to resort to model experimentation to develop knowledge of the subject.

THE FIRST LARGE CAVITATION TUNNEL

Sir Charles Parsons had continued his interest in model testing, and in 1910 started testing work in a new cavitation tunnel, which was the forerunner of the type in use today. The tunnel had a measuring section of 2'3" x 2'6" in which model screws of 12" diameter were tested, thus comparing in size with many modern establishments. Parsons continued testing until his death in 1931, and in addition to ad hoc testing of designs of warships and liner propellers, he also tested standard series of propellers having differing pitch ratio and blade area ratio.

Fig. 2.

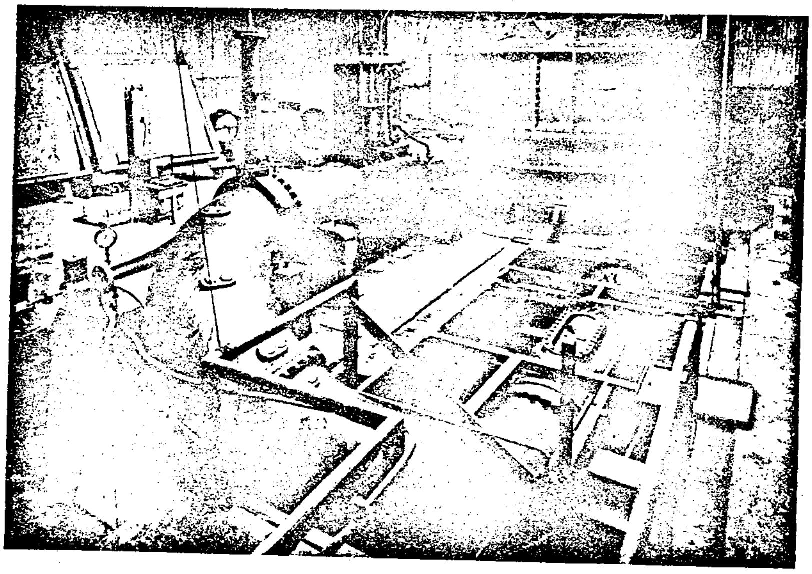


FIG.2. -Parsons' large cavitation tunnel (1910). General view

His results were presented as a series of diagrams recording efficiency, slip and a factor $K = \frac{P}{V^3}$ which can be related to the better known Bp value $\frac{NP^{\frac{1}{2}}}{VA^{2.5}}$ used today representing propeller loading. It is perhaps unfortunate that these diagrams were not publicised during Parsons' lifetime, and were only made available in 1951 when Professor Burrill gave the Parsons Memorial Lecture to the Institute of Marine Engineers, entitled

"Sir Charles Parsons and Cavitation". Ref.1.

EXPANSION OF TESTING FACILITIES.

During the period between the world wars the cavitation erosion problem assumed sometimes alarming proportions. Some Atlantic liners were having their propellers replaced after only one or two double crossings at full power because of the enormous cavities which were appearing on the blades. Fig. 3.

The effect of this was firstly to seek propeller materials with greater resistance to erosion, and secondly to accelerate the theoretical and practical research into the problem. Thus cavitation testing tunnels began to appear at many of the leading ship model testing establishments, notably in the U.S.A., Holland, Sweden, Germany, and the United Kingdom.

These tunnels were basically similar to the Parsons tunnel, some smaller in size, but all embodied refinements in control and measuring equipment.

While much useful basic research work was carried on with these facilities, the actual prediction of erosion in any specific case was still not possible. This was because the tests were carried out in a uniform velocity stream representing the mean speed of advance of the water through the propeller disc, and initially no efforts were made to simulate the wake variation which occurs behind the hull. However, useful information was obtained on the physical nature and various types of cavitation and the importance of these types so far as propeller damage is concerned.

Ref. 3.
Ref. 4.

PHYSICAL NATURE AND TYPES OF CAVITATION.

If the local pressure in the fluid on, or near to, the propeller blade falls below the vapour pressure of the surrounding fluid, vaporisation takes place in the form of cavities. These cavities, which may take different forms depending on the operationsl conditions applying, will collapse upon entering a region of higher pressure. In extreme cases their collapse may be violent leading to damage to the surface of the blades.

The types of cavitation normally encountered are :-

Sheet Cavitation in which fairly large areas of the blade are denuded of water in proximity to the surface. This type of cavitation is not normally harmful to the blade surface except when the sheet withdraws violently.

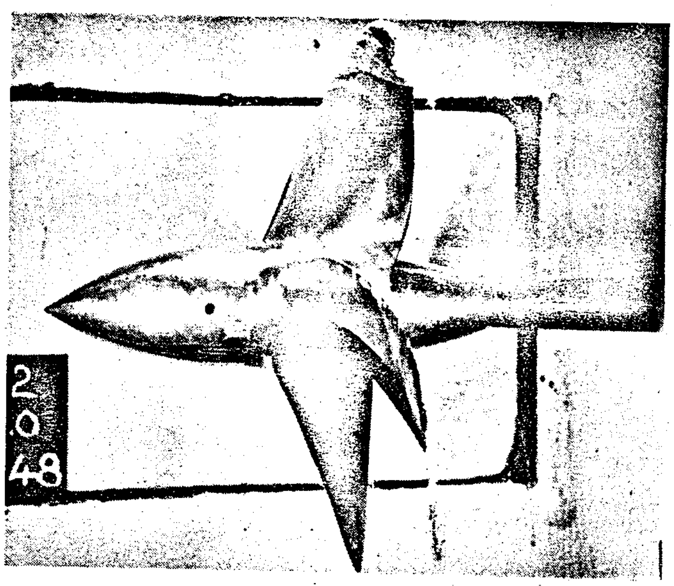


Fig. 4.

Cloud Cavitation has the appearance of a fine mist, and is believed to consist of large numbers of small bubbles. This type can be harmful if present on the blade surface and should be avoided if possible.

Fig. 5.

Bubble Cavitation is easily recognisable by large detached bubbles imploding on the blade surface. This is the most dangerous type and should be avoided.

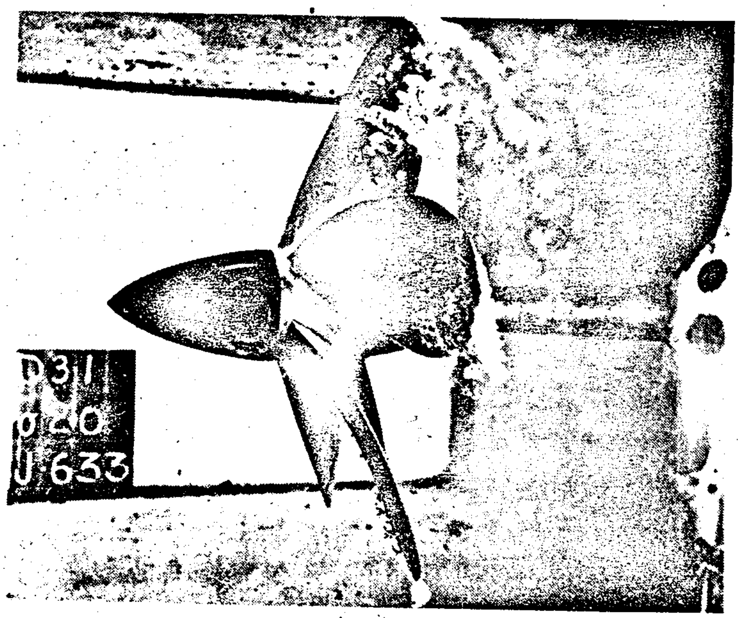
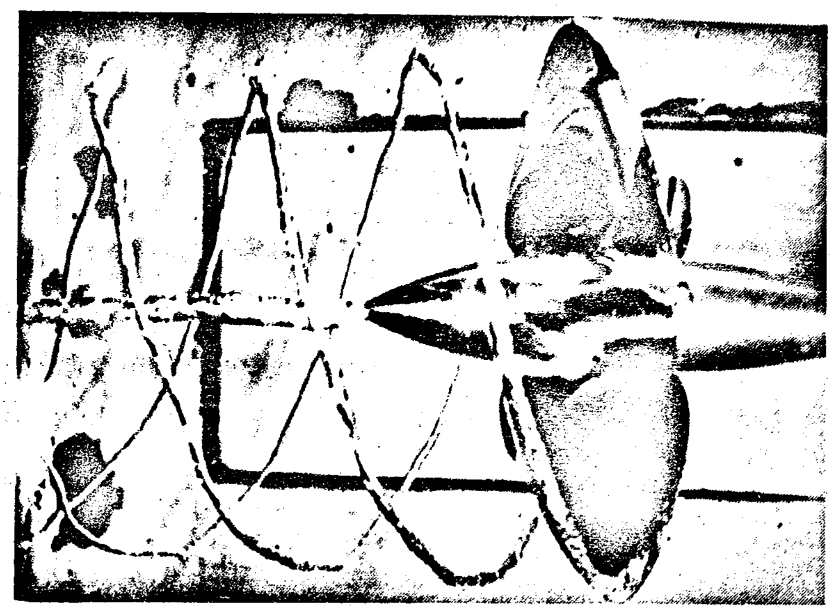


Fig. 6.

Vortex Cavitation is the long thin vortex which appears from the blade tips or propeller cone. Not normally troublesome unless the vortex breaks down on the hull surface, or on the nose of the rudder or rudder horn, when erosion of the steel plating may occur.

Fig. 7.



PRESSURE DISTRIBUTION CALCULATIONS.

While the model experimental work was developing, advances in the theoretical consideration of the subject of the pressures present on the blade surfaces were being made. The vortex theory method of analysis of propeller action had reached a stage where it was possible, under normal design conditions, to estimate the thrust and torque at each radius from the lift and drag characteristics of the blade section profile. When these data were used in conjunction with pressure calculations of the Theodorsen type it was possible to estimate on which areas of the blade the suction would be sufficient to cause cavitation, i.e. when the value exceeded the vapour pressure of the water.

Fig. 8.

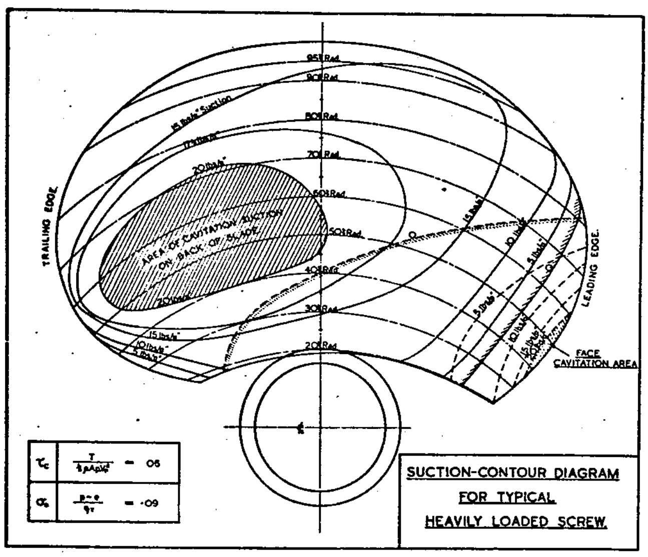


FIG. 8

It was thus possible to compare, in the uniform stream, the results of experiment and calculation, but the examples were few, largely because the calculations were arduous and lengthy and had to be carried out by hand at the time.

The use of such calculations in conjunction with test results in uniform stream, and with full scale experience from the observation of erosion patterns on propellers after periods in service, resulted in the widely used simple cavitation diagram published by Burrill in 1943. Ref. 2.

Fig. 9.

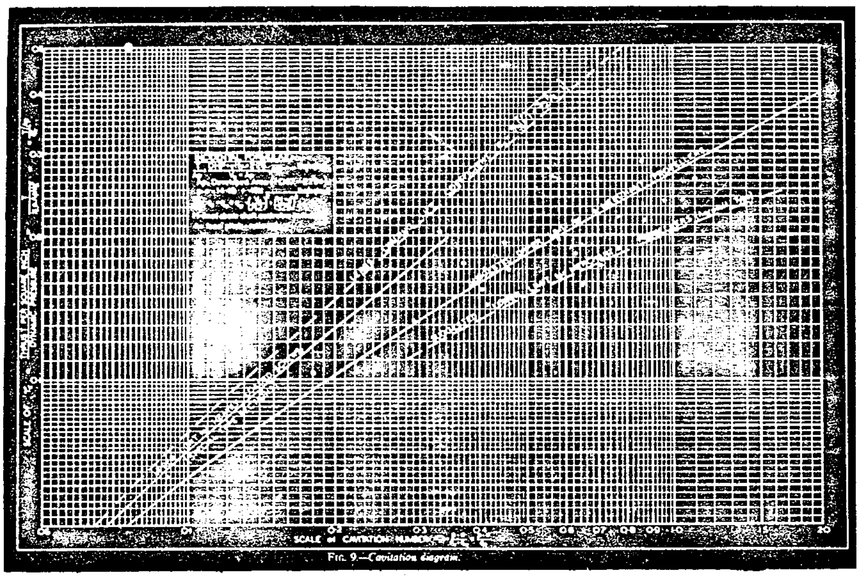


Fig. 9—Cavitation diagram.

After trying many methods of plotting his data it was found most convenient to plot a limiting lift coefficient τ_c against a corresponding cavitation number σ_o. Guidance lines were chosen from the results of known successful and unsuccessful propellers, and the use of these enabled the designer to choose a value of blade surface area which was likely to afford a reasonable margin against harmful cavitation under the chosen operating conditions of thrust and immersion. In using this diagram it must be remembered that the guidance lines apply to "families" of propellers having similar blade width distribution, types of blade section profiles and radial pitch distributions. In general very satisfactory results have been achieved by the application of this diagram, but occasionally, for example, when an unusual wake distribution exists, the surface area, or blade widths at the outer parts of the blade, may not be sufficient to avoid local cavitation erosion.

WAKE REPRESENTATION

The influence of the non-uniformity of the wake stream entering the propeller disc was appreciated to be a significant factor on screw propeller performance, from the results of wake distribution measurements behind model hulls carried out in the 1930's. It was not until the late 1950's, however, that such wake surveys began to become a regular feature of model tank testing, and efforts were made to consider cavitation performance in the light of the results of these experiments.

Experimentally this was first done by varying the conditions of the uniform water speed in the cavitation tunnel to represent the extremes of wake and cavitation number in the propeller disc, for example, at the upper arch of the aperture where the water speed is usually lowest and the head of water above the propeller blade is lowest. While helpful, this method had drawbacks in that it was impossible to account for the effects of transition from one wake region to another, which affects the formation and breakdown of cavitation.

Methods were devised of simulating the velocity distribution in the cavitation tunnel, and these are:-

(1) The flow regulator as used by Netherlands Ship Model Basin;

(2) Wire mesh grids to impose the necessary retardation of flow in certain areas;

and

(3) A dummy stern form in conjunction with wire grids.

Fig. 10.

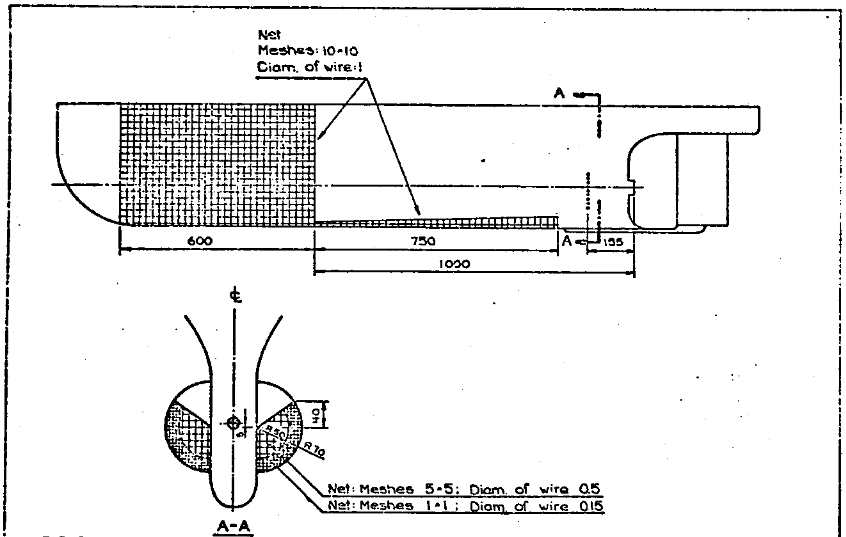


FIG.10.

In each case it is only the axial components of the wake that can be reproduced, but it is believed that by using the third method some approximation to the tangential components will be represented.

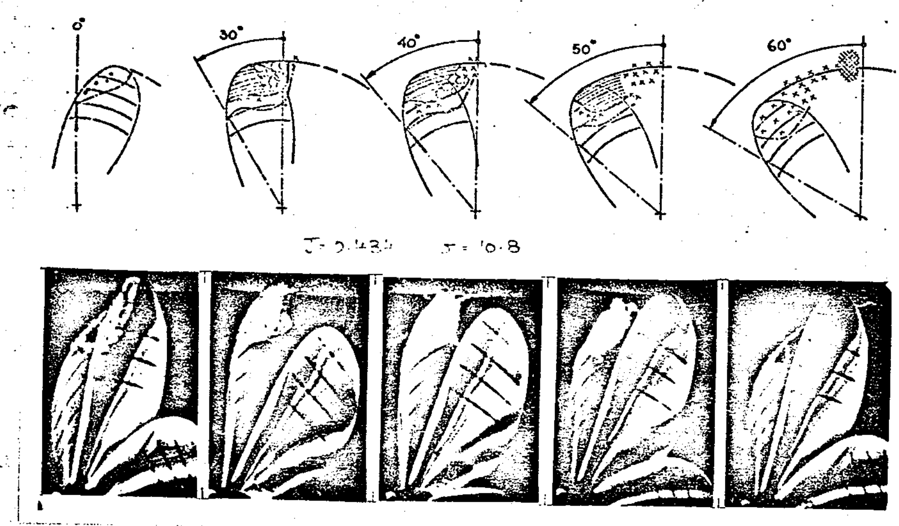
In considering tests under such conditions it must be remembered that there is a scale difference between model and ship, which cannot be properly accounted for because it is impossible to represent the correct Froude number, Reynolds number, and cavitation number simultaneously.

TESTS IN SIMULATED FLOW CONDITIONS.

Cavitation tunnel tests under simulated flow conditions were first carried out commercially in the late 1950s. The extent and apparent severity of the cavitation which was observed on the model propeller blades caused considerable alarm, and evoked strong recommendations from the experimenters to modify propeller designs which, in many cases were of families which had given satisfactory service in the past.

It was soon realised that not all cavitation led to erosion, and that considerable systematic correlation with full scale performance was essential before accurate full scale predictions could be made from visual observations of models in the cavitation tunnel.

Fig. 11.



This type of correlation requires patience, time, and expense, as it may be some years before the effects of cavitation erosion can be properly identified, and the interception of subject ships in drydocks is not by any means easy. However, in the author's company strong endeavours have been made to collect such data, and records for over one hundred and fifty examples are now filed.

PAINT TESTS

These records together with other investigators' experience, have greatly assisted the prediction of full scale erosion from visual observations of cavitation tests, but this is not by any means a simple matter, since minor changes in blade form, which can easily be present on the small models, can have a critical effect on the onset of cavitation.

The most revolutionary step in this field, in the author's opinion, however, was the introduction of the paint test technique believed to have been first used by the Swedish State Tank at Gothenburg. This consists of applying a thin coat of paint or other coloured fluid to the outer surfaces of the model propeller blades, then running the model in the cavitation tunnel under steady, controlled conditions for 30 minutes. At the end of that time the effects of any severe cavitation can be observed by erosion of the paint on the blades.

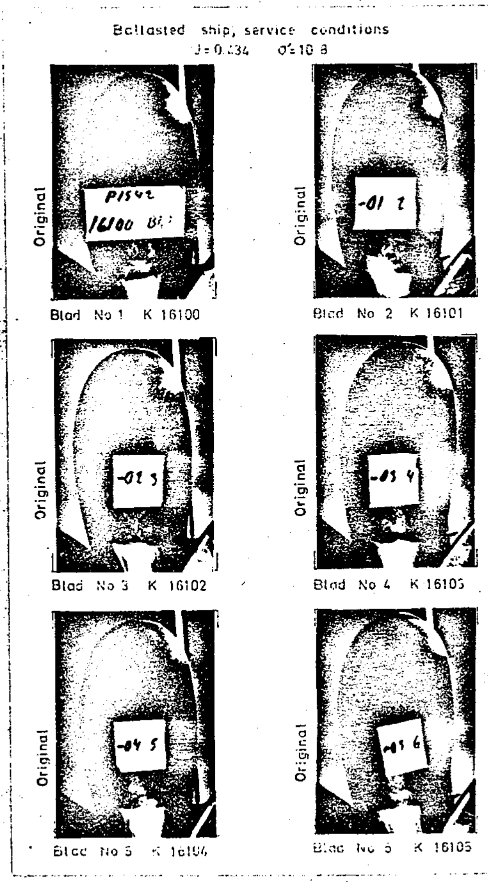


Fig.1

Examination of full scale propellers after periods in service has revealed remarkably good comparisons with the results of paint tests.

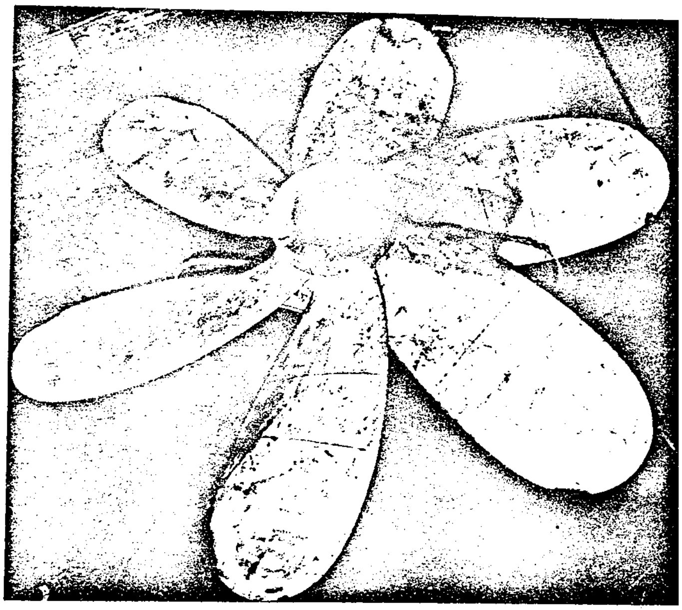


Fig.1

The technique has been adopted at other testing establishments, but it is strongly believed that ship/model correlation experience with every tunnel is essential before full scale predictions can be accepted, because fundamental differences between testing methods may influence the results.

Fig.1

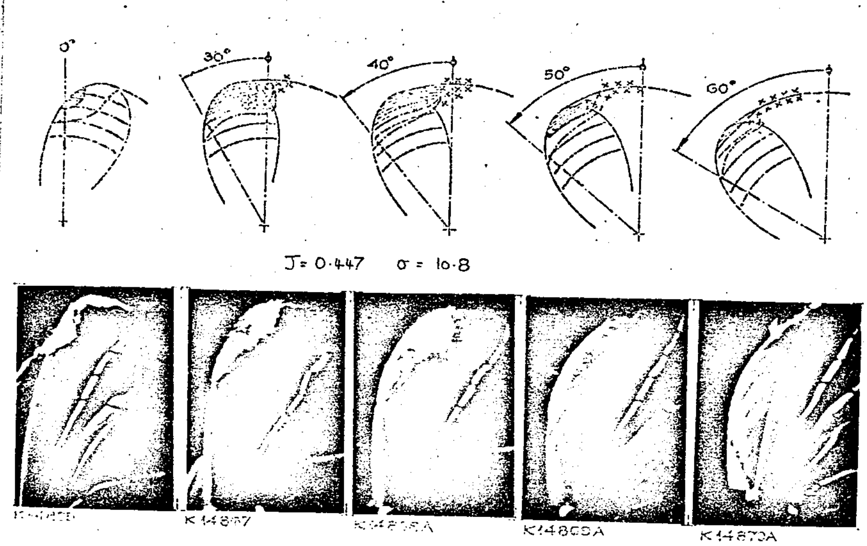
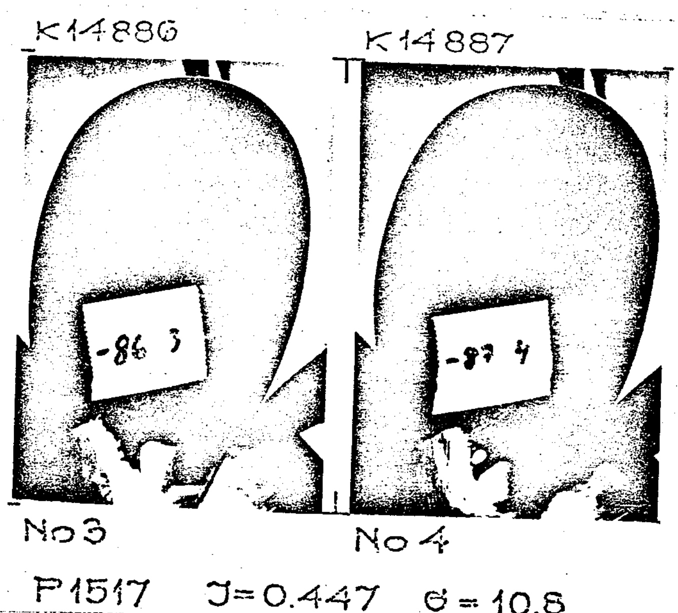


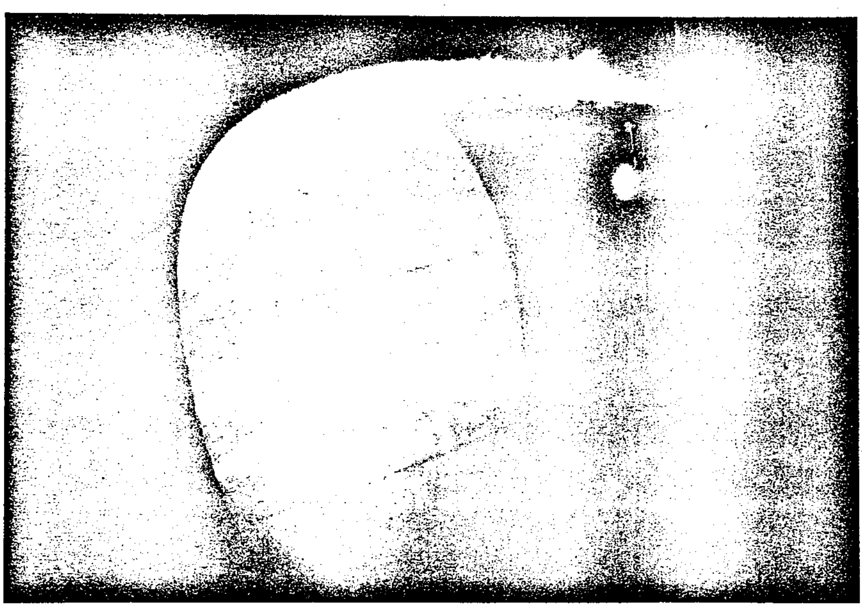
Fig.1



FULL SCALE VISUAL OBSERVATIONS

In recent years some very fascinating, and most valuable, work has been performed on the subject of full scale observation of propeller cavitation at sea. This is done by installing two windows in the ship's hull below the waterline, directing through one a stroboscopic light, and through the other a camera for photographing the cavitation under varying operating conditions.

Some of the results of this work, carried out by the research department of Det Norske Veritas, have been published, and excellent correlations with cavitation tunnel photographs and sketches have been revealed.



Ref.5
Fig.16

Fig.17

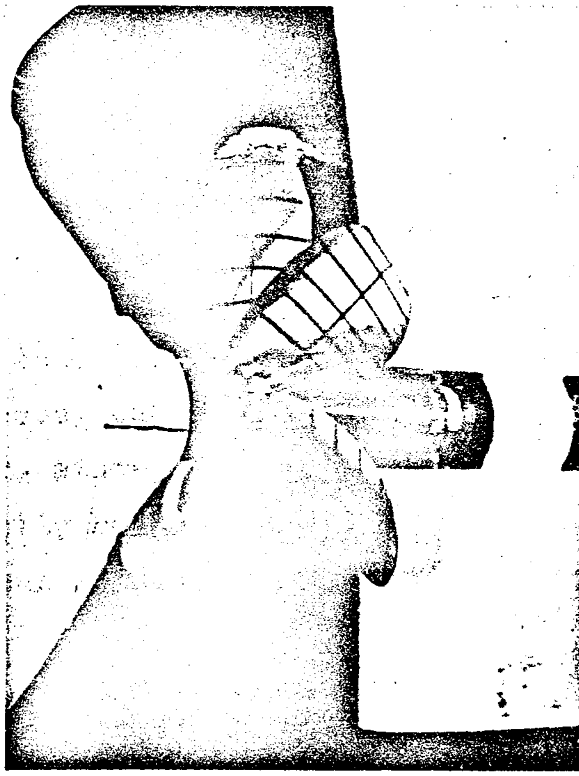


Fig.1

Fig.16

Fig.16

FURTHER THEORETICAL STUDIES

The advent and development of mechanical methods of calculation, and digital computers, has eliminated the time consuming aspect of carrying out the calculations referred to earlier to determine the thrust and torque characteristics of blade sections, and the associated pressure distributions. With a knowledge of the wake distribution it is now possible to perform such calculations at a number of angular positions during each revolution and thus to consider the fluctuations in the forces and pressures during each revolution.

No suitable non-steady lifting surface theory is available which might adequately represent the complete cavitation picture, but the application of two dimensional lifting line theory on a quasi-steady basis has been used with reasonable success. Comparisons with model/theory/full scale have given real hope of being able to predict cavitation from calculations, and it has been possible to embody some of this work into routine propeller design calculations.

Ref.6

The position at present with regard to erosion, the second harmful effect of cavitation, can therefore be summarised as follows :

1) In the varying wake stream behind present ship forms, particularly single screw forms, it is almost impossible to avoid some cavitation taking place.

2) There is, however, reasonable chance of predicting cavitation which might lead to erosion, either by model testing or calculations.

3) Steps can be taken to minimise erosion, either by alterations to the propeller design, or more positively by alterations to the hull form to improve the wake distribution.

4) Attention to the propeller design will almost invariably lead to increase in blade widths resulting in some, possibly small, loss in efficiency.

5) It is recommended that more attention should be paid to the hull form to reduce velocity fluctuations through the propeller disc.

VIBRATION.

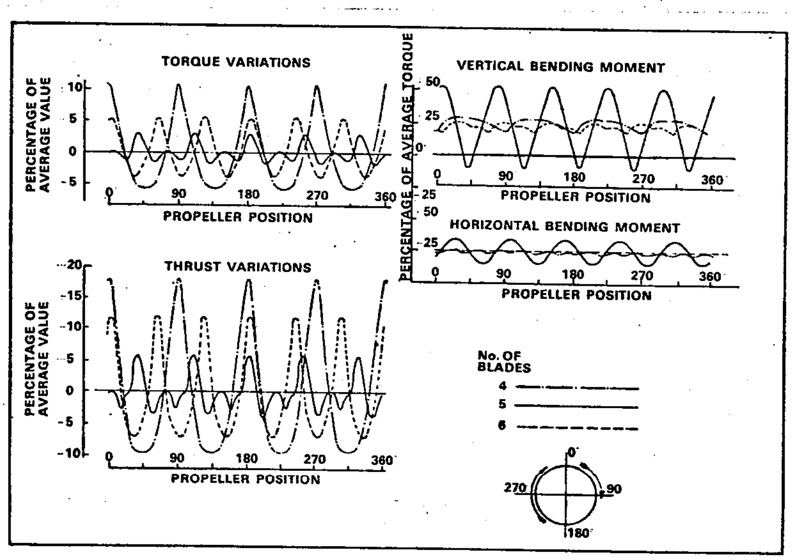
Ship hull vibration in various forms has presented itself in certain cases for many years, and has assumed a role of major importance in modern ships of high power, fitted with much delicate electronic control and navigation equipment. As the frequency of vibration is mostly coincidental with the product of shaft r.p.m. x number of propeller blades, or some function of this result, the vibration is usually described as propeller excited.

While some steps can be taken by design to reduce the excitation forces from the propeller, there will inevitably be fluctuations in these forces due to wake variations, and any resulting ship hull vibration should perhaps more properly be described as "wake excited vibration", since it is not the fault of the propeller that it should be asked to operate under such unfavourable conditions.

Irregularities in thrust and torque forces from the propeller during each revolution can lead either to axial and/or torsional vibration of the shafting which is transmitted to the hull via the shaft bearings or thrust block, or to direct hull vibration from the forces imparted to the hull structure by the passage of the blades.

In the normal course of operation there is a pressure field surrounding each blade which, even if no wake variations were present, would create an impulse as each blade passes the hull. The presence of a variable wake field causes greater fluctuations in the excitation forces, usually an increase in the high wake region at the upper and lower arch of the aperture on single screw ships, which increases the possibility of vibration taking place.

Fig. 18.



For many years the occurrence of hull vibration was associated only with propeller/hull clearances and with resonance between blade frequency and the natural frequency of the hull.

Changes in propeller blade number have sometimes successfully reduced or eliminated vibration, and increases in blade clearances have likewise sometimes effected improvements. It is now realised that the latter measures have only succeeded because the propeller blades have been moved into a slightly more favourable wake distribution. There have been cases when the clearances forward of the blades have been increased by alteration to the hull lines resulting in steep waterline endings, with worsening effects on the cavitation and vibration, thus indicating that the wake field has been unfavourably modified.

Conversely, the clearances forward of the propeller have been reduced by the addition of fairing in the aperture, with favourable results to the vibration performance.

Heavy vibration is sometimes accompanied by sharp noises heard near the stern of the ship, at blade frequency. It has been suspected that these noises were associated with cavitation as each blade passed close to the hull.

THE THIRD HARMFUL EFFECT OF CAVITATION.

Recent publications of the results of experimental work carried out in cavitation tunnels has shown that the excitation forces produced by the operation of the propeller are increased by a large factor when cavitation is taking place. Ref. 7. Ref. 8.

The ship vibration caused by fluctuating forces is the third harmful effect of cavitation.

This must be considered separately from the second effect, since the measures which can be taken to avoid erosion taking place do not necessarily eliminate cavitation completely, and it is believed that the residual cavitation can still create sufficient additional excitation force to cause vibration.

Experiments in which the pressure impulses were measured on a dummy hull in a cavitation tunnel with cavitating and non-cavitating propeller models, showed that the pressure fluctuations could be 12 times larger with the cavitating propeller depending on the propeller geometry, operating conditions and blade number. The influence of cavitation is relatively larger for propellers with higher blade numbers. Fig.19

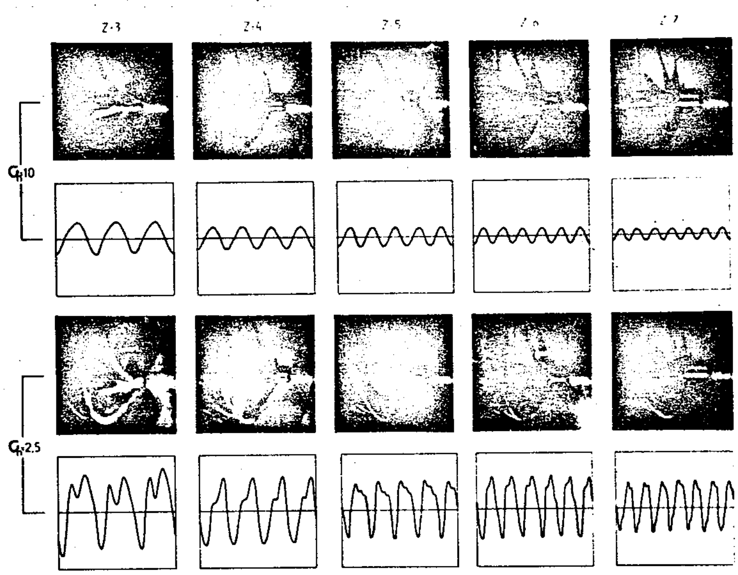


FIG. 19. Pressure fluctuations on centreline of hull as caused by different number of blades.

TESTING FULL SHIP MODELS & PROPELLER

Available calculation methods were inadequate to estimate the propeller induced pressure fluctuations under cavitating conditions, and once again it has been necessary to resort to model experiments to investigate the interaction between cavitating propellers and the ship's hull.

In such work, it is more important than ever to ensure that, not only the axial wake distribution, but also the radial and tangential distributions are accurately reproduced, and that the model propeller is operating under proper cavitating conditions.

Therefore facilities have been built in which large complete ship models can be tested with the propeller in operation at the correct cavitation number, Froude number, and advance co-efficient. Two methods have been adopted, one at the Swedish State Tank in which the complete model is placed in a large cavitation tunnel with a measuring section of 2.6m x 1.5m. The second is at Netherlands Ship Model Basin where a vacuum towing tank has been constructed, to test ship models up to 12m in length, 2.4m in width and 18 tons in weight. Ref.7

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FULL SCALE EXPERIMENTATION

Det Norske Veritas, in conjunction with Scandinavian Shipbuilders, Owners, and Experimental Tanks, have performed some valuable full scale measurements of hull forces in conjunction with full scale observations of cavitation, for comparison with model results. In due course, after comparison of a representative number of examples, it could be possible to estimate likely vibration from model tests, and in time, hopefully, from calculations.

PREVENTION AND CURE OF CAVITATION PROBLEMS

The cure of most cavitation problems lies in an improvement in the velocity distribution into the propeller. Experience has shown that high and low velocity peaks should be avoided, and that steep gradients from regions of high velocity to regions of low velocity, and vice versa, should also be avoided.

Examples of wake distribution are shown illustrating these features. Fig.20

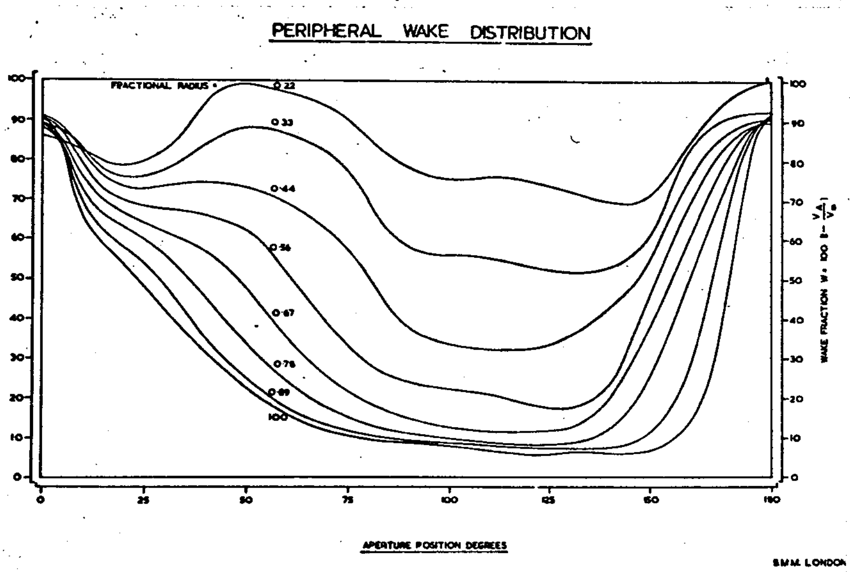


Fig.2

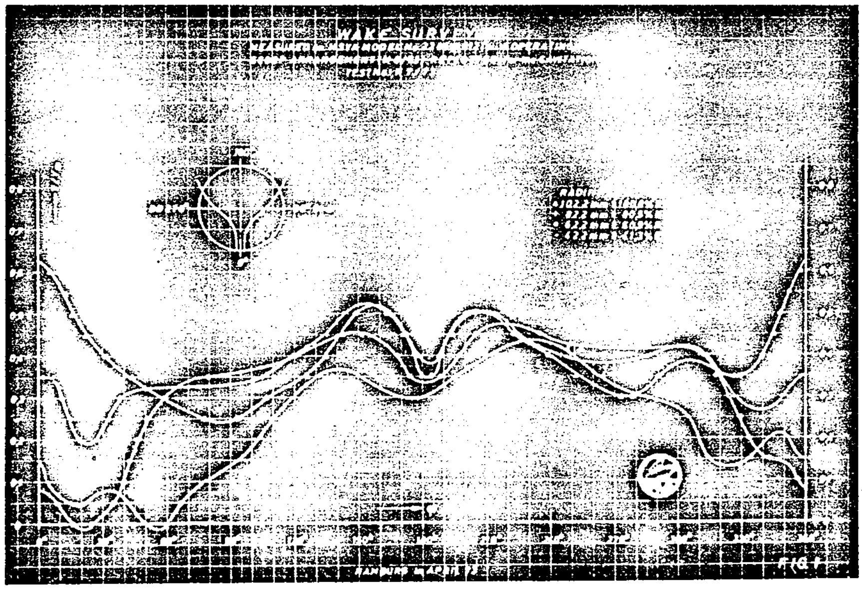
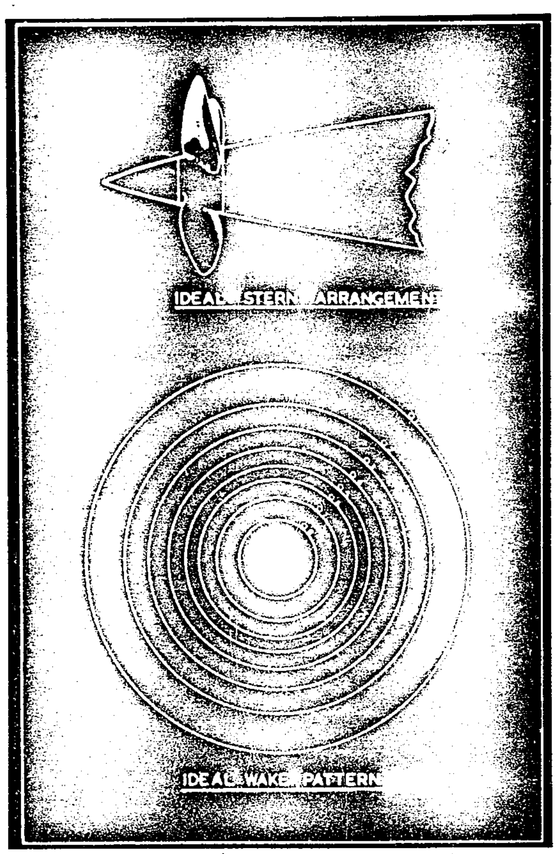


Fig.2



Prevention is always better than cure. Therefore efforts should be made to produce hull forms giving good wake distributions. It is not yet possible to be sure of good results without the use of model experiments, but there are certain rules which can be followed with advantage. These are :

1) Avoid steepening reflexes in the waterlines near the propeller, which might give rise to flow separation.

2) Keep the angles of run of the waterlines as low as possible in the upper arch of the aperture.

3) Make the waterline endings at the sternpost as fine as practicable.

4) Do not attempt to obtain large clearances forward of the propeller blades at the expense of fineness of waterline endings.

5) Wake surveys should be carried out as early as possible in the testing programme, and modifications to the lines made to effect improvements. This procedure is being practised more and more on the European Continent. There is little point in performing such tests when the ship is half built.

In cases when vibration and/or severe local cavitation erosion has been found to occur in service, the wake distribution can be modified by the use of fins, partial tunnels, or vortex generators. Each of these methods have been found to give success in isolated cases. An indication of their worth can be judged from model tests, but the true value usually is not confirmed until full scale tests have been made.

CONCLUSIONS.

Of the three harmful effects of cavitation, it can be said that the first - i.e. loss of thrust, is now not met with on normal merchant ships.

The second, that of cavitation erosion, is now not seriously troublesome. It can be anticipated by calculation and model tests, and steps can be taken to avoid serious effects. In so doing, it may be necessary to adopt increases in blade width resulting in small losses of efficiency. These losses could be avoided if better wake fields are provided in the propeller plane.

The third effect, that of vibration, is more serious. To avoid cavitation completely in an unfavourable wake field may be impossible, and in any case would inevitably result in very wide propeller blades with a consequent loss of efficiency, increase in weight leading possibly to other problems, and price.

It is recommended that greater attention should be paid to after body forms to improve the velocity distribution in the propeller disc.

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THE HARMFUL EFFECTS OF CAVITATION ON MARINE PROPELLERS

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FIGURES

1) Parsons' small cavitation tunnel.

2) Parsons' large cavitation tunnel.

3) Cavitation erosion on Atlantic Liner propeller.

4) Sheet Cavitation.

5) Cloud Cavitation.

6) Bubble Cavitation.

7) Tip vortex and root vortex cavitation.

8) Suction contour diagram for typical heavily loaded screw.

9) Simple cavitation diagram.

10) Dummy stern and wire grids in cavitation tunnel.

11) Simulated flow test results.

12) Paint test results.

13) Full scale propeller after service.

14) Simulated flow test results.

15) Paint test results.

16) Full scale cavitation at sea.

17) Cavitation test photographs.

16a) Full scale cavitation at sea.

16b) Full scale cavitation at sea.

16c) Full scale cavitation at sea.

18) Effect of number of blades on dynamic propeller forces.

19) Pressure fluctuations on centreline of hull, as caused by different number of blades.

20) Wake diagram - poor distribution.

21) Wake diagram - good distribution.

22) Wake diagram - ideal distribution.