STONE
MARINE
PROPULSION

Cavitation of Propellers

Introduction

Cavitation—its cause and effects—has been the subject of considerable research effort in the past, both as a general problem in hydrodynamics and in particular as an undesirable characteristic of marine propeller performance. With the trend to larger and faster sea transport, it has re-emerged as a factor that can and will have considerable influence upon the design philosophy of the propulsion engineer. Such philosophy will always benefit by the developments of more sophisticated materials and manufacturing processes, but these contributions are to some extent limited. Ultimately the problem is one of design, not of the propeller alone but of the propeller as an integral part of the propulsion concept—comprising the hull form, machinery and operational environment.

History

The problems of cavitation have existed since the screw propeller was first introduced to the marine environment, but not until the turn of the 20th century was the true nature of the phenomenon recognised.

From the trials experience of the Torpedo Boat Destroyer "DARING" and later the "TURBINIA" it was found that without sufficient blade area the propeller was limited in the thrust that could be developed. It was realised that the problem was one of loading—that when the pressure reduction on the back of the blades exceeded the combined atmospheric and static head pressures then the fluid would be disrupted, forming vacuous cavities. Once these cavities completely covered the blades then no further thrust could be developed. As a result various design criteria were proposed, the most notable of which were a limiting thrust and a limiting tip speed. Such criteria were simple and served only as guidance for the individual designer, who more often used his own experience and personal judgement to resolve the problem.

The means for studying the problem—the cavitation tunnel—together with the introduction of aero-dynamic principles to propeller applications then cast much needed light upon the subject, so that today, while there is still much to learn, our understanding of the subject is more complete. In particular, aerodynamic considerations revealed that the presence of cavitation was a function of the local variations in the blade suction magnitude rather than the area enclosed by the pressure curves, as was implied by the earlier thrust criteria. This led to the criterion of a limiting lift coefficient and its application revealed that a segmental section was superior to an aerofoil section from the cavitation aspect, which resulted in the adoption of such profiles at the more critical tip regions.

A more general form of this criterion was used to develop a consistent basis for the selection of the blade area. Before the 1939—45 war most merchant ship propellers were comparatively slow turning and moderately loaded. But with the advent of larger and more powerful main machinery—speed, power and revolutions increased rapidly, resulting in local patches of roughness and cavitation erosion. The problem was approached using cavitation charts such as shown in figures 1, which were based on a limiting lift co-efficient at 0.7 radius where the risk was then greatest. Although strictly applicable only to propellers of a single family, i.e. having the same general geometrical relationships, this chart provided a useful design criterion for many years and is still an extremely useful basis for comparison at the present time.

An important additional contribution to success in this field was the introduction of high strength copper alloys having much higher resistance to attack from cavitation erosion than the manganese bronzes.

Today the trend for more specialised ships having differing propulsion characteristics is evolving a need to consider each class of vessel on its own merits. For example, the container ship with a high performance requirement at a limited draught, and the lower speed super-tanker operating at two distinct and separate conditions—loaded and ballast, in both cases the working environment of the propeller is so severe that the presence of cavitation must be considered inevitable and the designer seeks more to keep a check upon the harmful effects of cavitation than to eliminate the problem in its entirety. The analytical methods currently available and the development of the high speed computers are proving invaluable aids to such work.

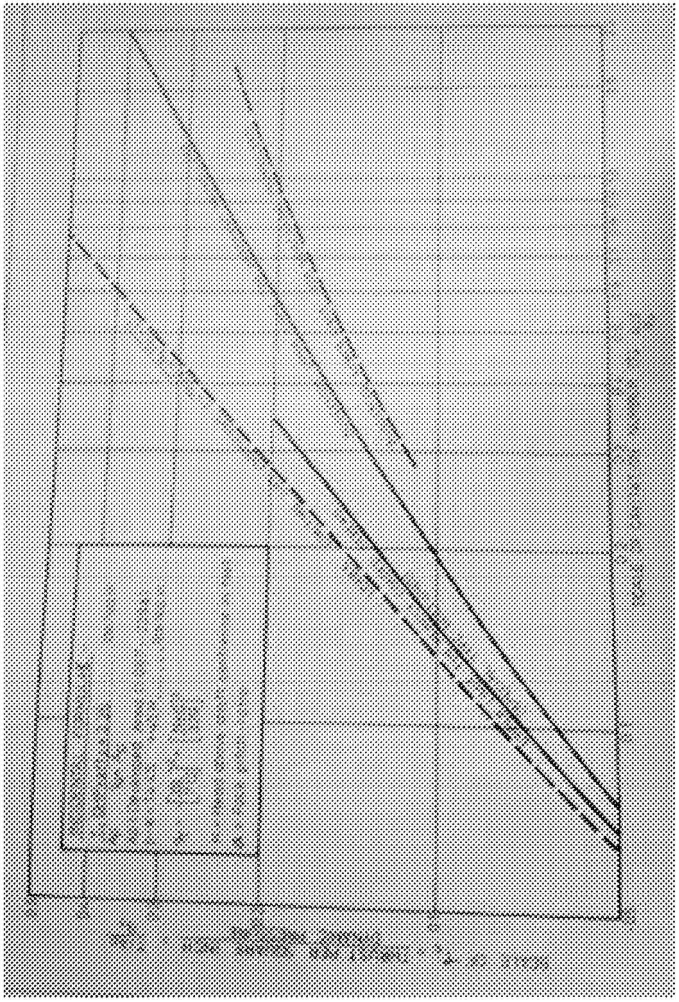


Figure 1 – Cavitation chart

Definition

A liquid has the property of vaporising under given conditions of temperature and pressure, as shown in Figure 2. Boiling is an example of this, the water at atmospheric pressure vaporising when the temperature reaches 100°C. Similarly, vaporisation occurs at a given temperature if the pressure is sufficiently reduced and in this particular case is known as cavitation.

Now the marine propeller exerts thrust by setting up a variable pressure field about the blade surface, a suction on the back of the blades and a pressure on the blade faces, the major contribution to the resultant thrust coming from the suction side. If the suction is so great that the absolute pressure approaches the vapour pressure of the water at that temperature, then vaporisation takes place and small cavities form in the water. These cavities contain water vapour and dissolved gases and will collapse, often violently, on meeting a region of higher pressure in the flow stream.

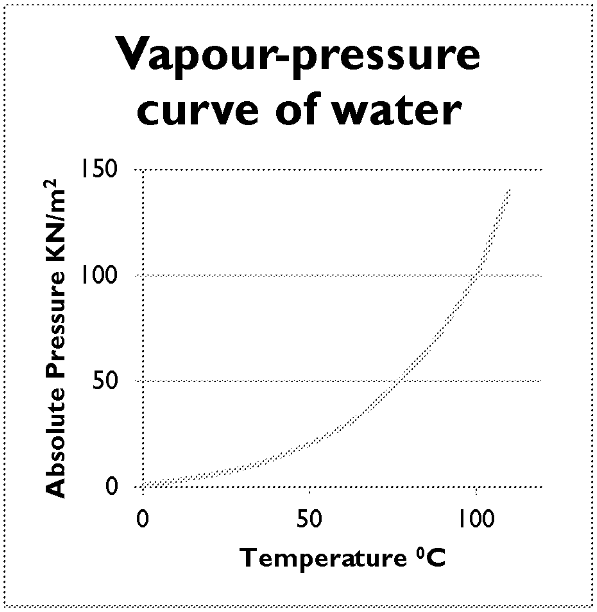


Figure 2. Liquid above the curve, vapour below the curve.

Cavitation types

Cavitation takes several forms and in relation the marine propeller it is usual to define these forms by their physical appearance. There are four main types of interest:

Sheet Cavitation

Cloud Cavitation

Bubble Cavitation

Vortex Cavitation

Sheet Cavitation takes the form of a thin stationary sheet usually commencing at the leading edge of the blades, and can occur on both back and face of the blade, separately or simultaneously, depending upon the conditions.

Cloud Cavitation—in certain conditions sheet cavitation breaks down into a form usually known as "cloud" or "mist" cavitation.

Bubble Cavitation, as the name implies, is the formation of distinctive bubble cavities which are generated in the mid-chord region of the blade backs.

Vortex Cavitation has the appearance of a stranded twisted rope and can be present at either the blade tips or the boss.

Effects

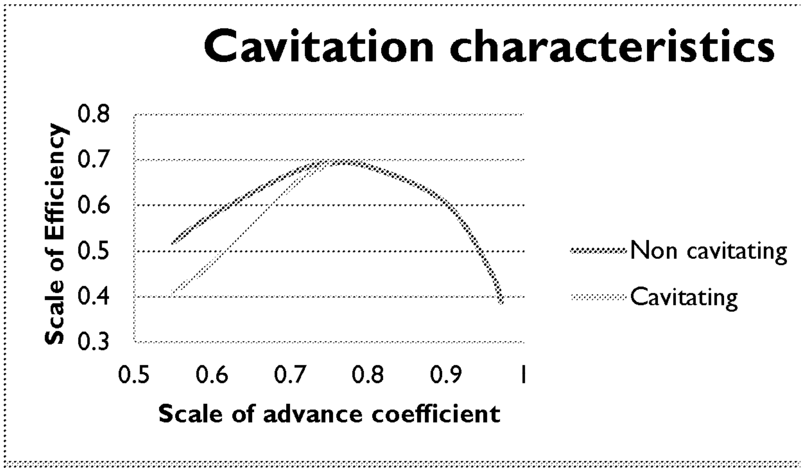
There are four effects of cavitation, all of which are detrimental:

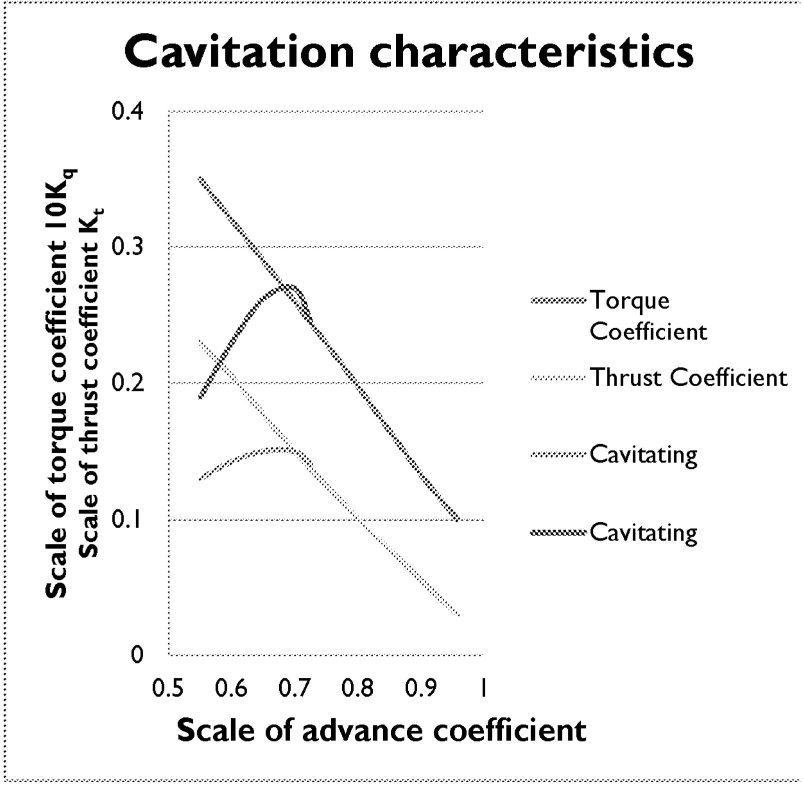
Performance suffers because the water can only support a limited suction dependent upon the conditions. If the blade suction has a potential magnitude in excess of this limit, then that potential cannot be realised. The thrust is thus decreased and the efficiency falls, as illustrated in Figure 3.

Erosion of the propeller material will occur if the cavities collapse in the proximity of the blade surface. During collapse considerable pressures can be generated, capable of such intensities that no material can withstand the attack. Other forms of attack, such as corrosion and electrochemical action, are closely related to erosion. A typical example of erosion is shown in Figures 4.

Noise is produced during cavity collapse which can have considerable nuisance value, particularly in vessels with accommodation aft.

Vibration can be induced by cavitation due to the unsteady nature of the phenomenon involving large fluctuating forces. Recent research has indicated that cavitation has considerable influence on propeller induced pressure fluctuations.





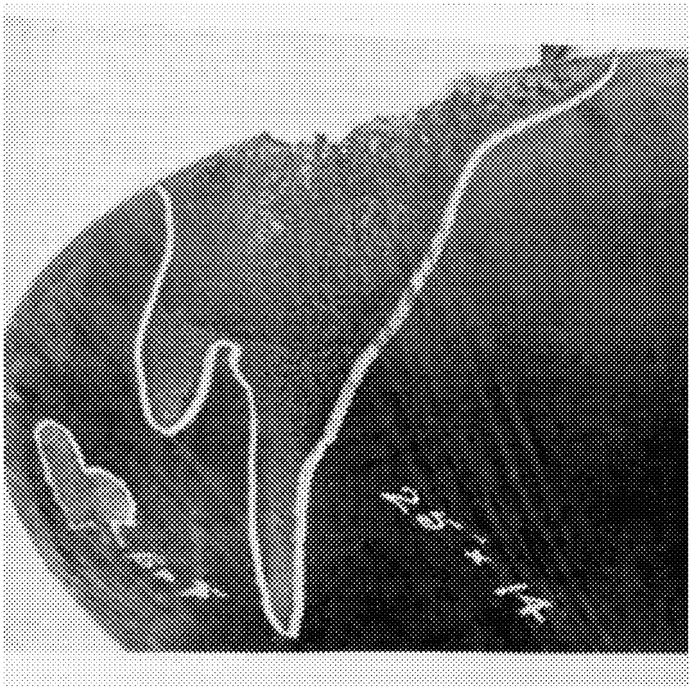


Figure 4

HYDRODYNAMIC CONSIDERATIONS

The pressure distribution

Since World War II cavitation has been investigated increasingly by means of model tests in the cavitation tunnel. Theoretical studies are now also being applied as improved facilities become available, e.g. by examination of the calculated pressure field about the blade surface. The general form of the pressure distribution about a propeller section is shown in Figure 5 and is plotted as shown for convenience. The cavitation index, designated by σ, indicates the suction limit as determined from the operating conditions, so that if the suction anywhere exceeds this limit then cavitation will occur and this is demonstrated in Figure 6.

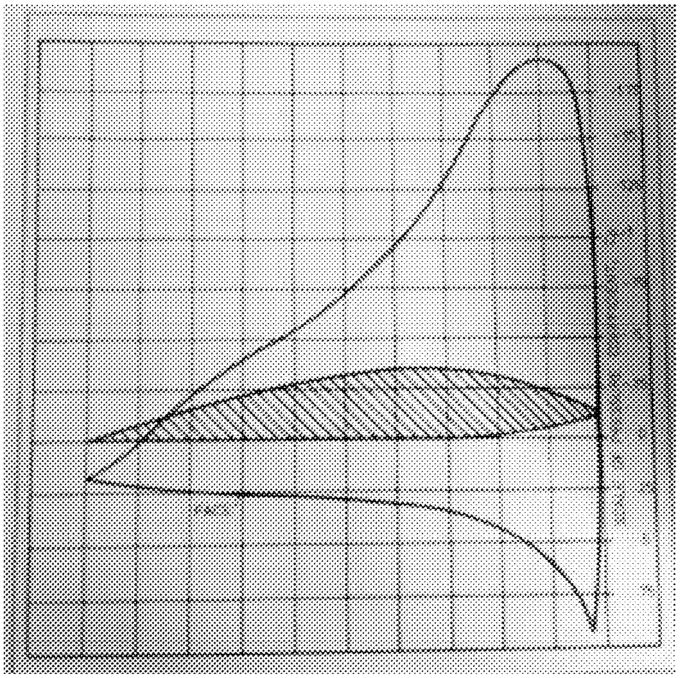


Figure 5

Since cavitation is dependent upon the shape of the pressure curve in relation to the cavitation index, the parameters that influence these factors can be examined and their effects evaluated. Basically such parameters can be found in two general groups:

the propeller environment

the propeller geometry

and of these the propeller designer can control only the blade geometry.

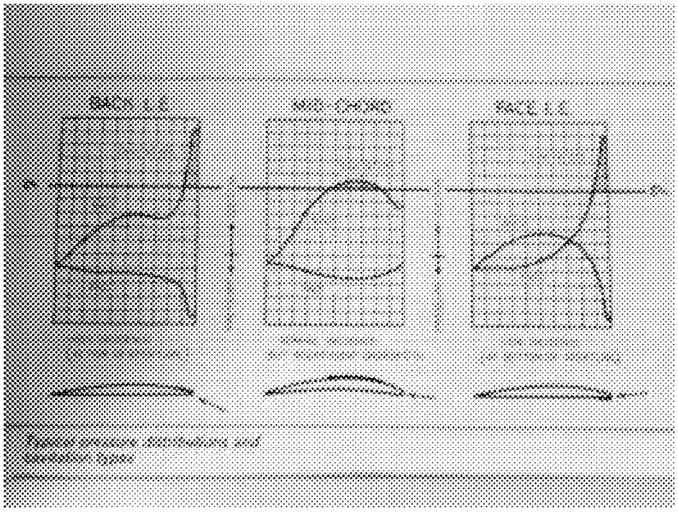


Figure 6

Environment

The propeller environment has two main effects.

First, it establishes the incidence of flow to the blades which together with the blade geometry determines the shape of the pressure curves for a given profile. Referring now to Figure 7, a simplified velocity diagram for a propeller section, the incidence is dependent upon the speed, wake and revolutions. When designing the propeller only one such condition can be considered, generally the loaded service condition for which the best possible efficiency is required. This is not always the most onerous condition from the cavitation point of view and so design charts, Figure 1, incorporate safety margins which normally account for differing conditions.

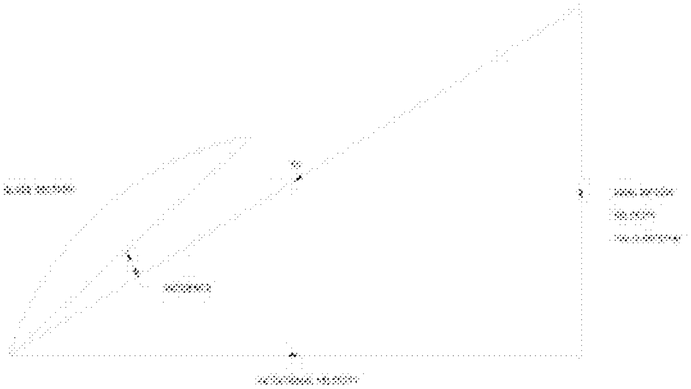


Figure 7

The other important feature is the vessel's draught which determines the cavitation index—the limiting suction. The cavitation index is defined by:

$$\sigma = \frac{P + P_i}{\frac{1}{2}\rho V o^2}$$

where :-

P is the difference in pressure between the atmosphere and the vapour pressure of the water:

P_i is the static pressure at the section in the fluid;

$\frac{1}{2}\rho V o^2$ is the stagnation pressure at the section.

It is apparent that P and V are constant for a given condition. P_i is a function of the draught and position of the blade in the aperture—the deeper the propeller is immersed the greater the safety against cavitation. Because of this the ballast condition is important, particularly for large tankers, for although at the loaded draught any cavitation will normally be harmless, at the ballast draught the cavitation can become extremely severe.

Influence of wake

Due to the presence of the hull the flow of water into the propeller disc is never uniform, as can be seen in Figure 8. The contours show lines of constant wake measured normal to a transverse vertical plane through the propeller axis. Ideally, the wake at each radius should be circumferentially uniform since each section would then be working at a constant incidence throughout the revolution. However, in practice there is a circumferential variation in wake for a typical outer section, is such that the incidence is continually changing as the blade sweeps through each revolution. It is significant that the highest wake and consequentially the greatest incidence occur at the top of the aperture where the cavitation index will be a minimum.

In the design process the sections at each radius is considered to operate at the mean of the circumferential variations and then as the wake increases or decreases about this mean value, so are the incidence and pressure distribution affected. It is therefore possible that if the wake variations are large enough a section can experience both back and face cavitation in turn during each revolution.

The determination of the circumferential mean wake at each radius is therefore critical, for any bias would clearly increase the cavitation risk on one side or other of the blade.

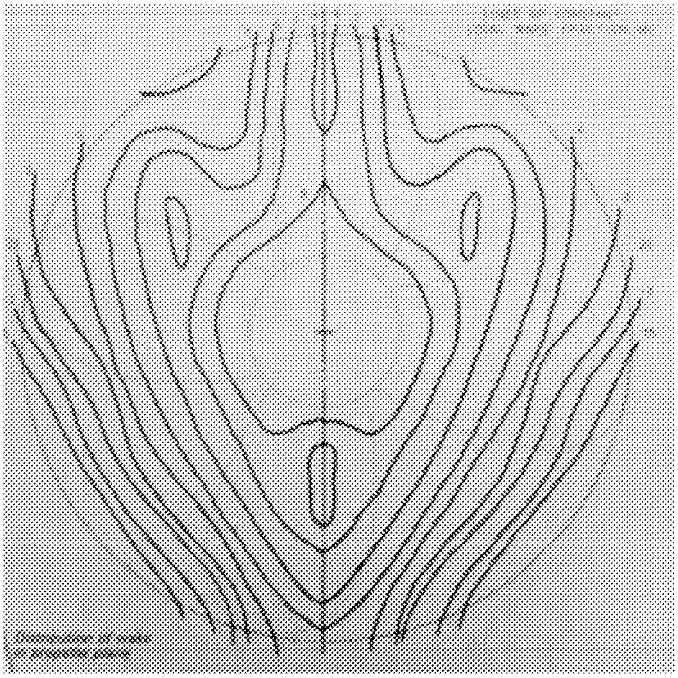


Figure 8

Blade geometry

For a given flow incidence the geometry of the blade determines the general shape of the pressure distribution about its surface. The main parameters involved and their effects can be briefly summarized

- the effect of increasing thickness is to increase the cavitation risk;
- the effect of increasing chordwidth is to reduce the cavitation risk;
- the effect of camber* is more complicated, generally increasing the cavitation risk at the back midchord and face leading edge regions, but reducing the risk at the back leading edge;
- the form of the blade edges is critical,

These are only general comments and must always be considered In relation to each particular case.

** Camber is defined as the centre-line about which the thickness body is evenly distributed.*

Design

Current propeller design practice is based upon obtaining the maximum possible efficiency in the imposed environment consistent with satisfactory strength and cavitation characteristics. Each has conflicting requirements and so the design process is in reality a compromise.

Ideally, from the cavitation viewpoint, the blades should be cambered and pitched for shockfree entry, have minimum thickness and sufficient chordwidth to restrict any suction peaks below the local cavitation index. In practice this is not possible.

The camber and pitch are chosen from considerations of minimum drag and highest efficiency at the specified operating condition. The resulting incidence gives a generally satisfactory balance between face and back cavitation which allows each design to be established with some confidence, provided that sufficient surface area is originally specified.

The thickness is determined from strength considerations and is always a minimum consistent with such requirements. It is here that the quality of the propeller material can prove of considerable benefit for with the development of higher strength alloys, the thickness can be reduced with a consequent decrease in the surface for the same cavitation risk, resulting in a more efficient and competitive propeller design.

With the camber, pitch and thickness established mainly from other considerations, attention is given to the surface area parameter for controlling the cavitation risk. The difficulty is that all geometrical features of the propeller are closely interdependent, so that any changes made to the area, for example, will necessitate a complete reappraisal of the design. It is necessary therefore to assess the required surface area at the earliest possible stage in the design but it is somewhat of a paradox that an accurate assessment is only possible when the final details of the propeller have been established. In the past this proved no great difficulty and it is only with the increases in power, wake fluctuations and draught variations that the problem has become so much more complex.

The surface area is chosen using a chart such as Figure 1, based on the loaded service condition, which incorporates a margin sufficient to account for normal variations in wake and draught. However, for severe wake variations and very large changes in draught, normal use of the chart will prove inadequate and such conditions must then be examined in more detail.

One can ensure a satisfactory propeller from the cavitation viewpoint simply by specifying a very large surface area in each case. However, the efficiency of the propeller is very closely linked with its surface area, see Figure 9, so that a high cavitation safety margin because of the ample surface results in a penalty on the speed or fuel bill. A compromise is made—the designer strives to keep the area to a minimum consistent with a satisfactory cavitation performance. As a result, the fine balance achieved can be easily disturbed by some unforeseen feature as for instance localised regions of severe wake—leading to erosion of the blade material, and it is for this reason that close collaboration between hull designer and propeller designer is so important from the earliest possible moment.

The determination of a satisfactory cavitation performance is somewhat arbitrary, being primarily a judgement guided by previous experience; however, the increasing use of model testing has brought benefits in both propeller research and design. It is becoming accepted practice in many quarters to investigate the wake field at model scale and then examine the model propeller cavitation performance in the water tunnel. Nevertheless, it must be emphasised that in both cases no acceptable full scale correlation has yet been established. This means that the results of the model wake survey and the cavitation patterns seen on model scale do not necessarily represent those of the ship. Such results should always be considered on a guidance basis only until correlation can satisfactorily explain the ship/model discrepancies.

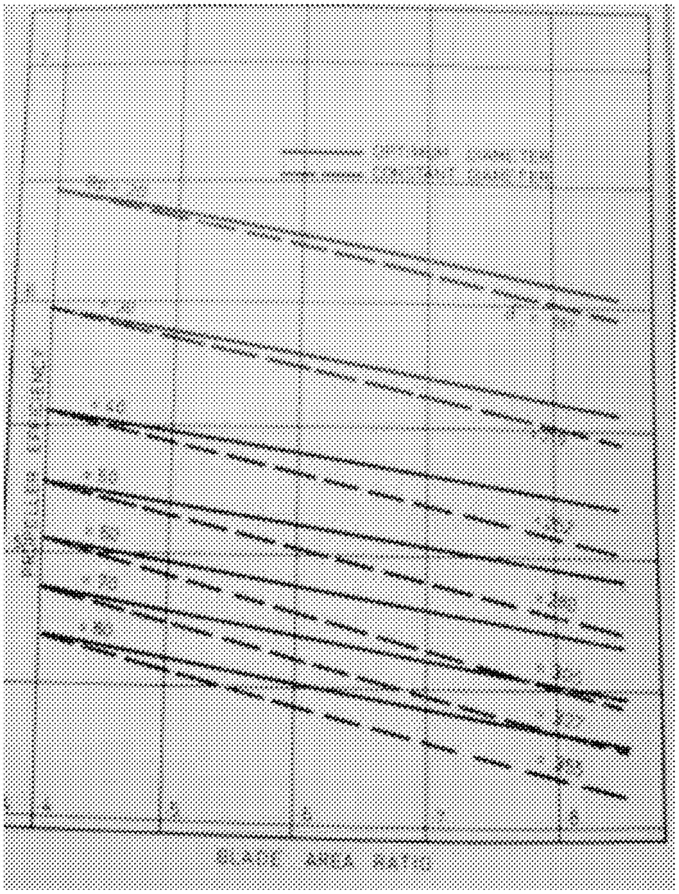


Figure 9 — efficiency-area relationship, Troust 'B' series 4 blades.

Today, with the development of the computer, cavitation is being investigated by examination of the pressure distribution about the propeller surface. Simple mathematical models have given encouraging results when compared with both model patterns and full—scale erosion records, such analysis indicates that the propeller geometry should be considered as a whole in order to achieve the most efficient propeller free from the harmful effects of cavitation, for increasing the area alone can prove economically prohibitive.

There is however a limit to what the propeller designer can achieve with the variables available and as a result the need to collaborate with the ship designer to control the environment—in particular the wake field—has become increasingly apparent in recent years.

Damage

Any deformation of the blade geometry—particularly in the more critical tip region—may be sufficient for erosion to develop. If the leading edge is affected, as it usually is, then because the form of the edge is extremely sensitive where cavitation is concerned, erosion of the material in that region will invariably result. In such cases the propeller can be repaired by welding the erosion and restoring the geometry to its original condition, sometimes without removing the propeller from the shaft.

The uncertain and variable nature of the flow behind a ship's hull is such that no propeller design can ever be considered completely safe from cavitation attack. For example, local wake "hot spots" or disturbed flow from a hull protuberance in way of the propeller disc, both of which are beyond the influence of the propeller designer, can result in erosion, in this event use is made of the critical nature of the nose form so that a small modification to ease the local flow conditions will often successfully eliminate the problem.

METALLURGICAL CONSIDERATIONS

The several manifestations of cavitation have already been mentioned. Erosion caused by cavitation is one problem with little obvious effect until the propeller is inspected.

In appearance, cavitation erosion is typically as shown in Figures 4. The general area of attack is often related to the direction of water flow, most normally being elliptically shaped with the major axis aligned in the direction of flow. Within any area of cavitation damage, there is no directionality. The surface of the damaged metal is very rough and resembles that of coke. Should cavitation erosion occur near a blade edge, curling of metal may result. This immediately gives some insight into the nature of the attack. Clearly since curling occurs, the mechanical forces at large are considerable: a portion of blade, say 20mm thick, may be bent through 30 degrees. Sections through cavitation erosion reveal cracks and fissures penetrating into the metal. It seems that these join up causing the loss of tiny pieces of metal. Thus, the attack is a form of mechanical damage and not a type of very rapid corrosion.

Further, examination of cracking associated with cavitation erosion suggests that the basic agency promoting deterioration of the metal is fatigue. As with fatigue, the influence of corrosion is secondary though possibly important.

All materials, metallic or not, can suffer from fatigue damage and certainly this applies equally to cavitation erosion. Although it is far better to prevent erosion by eliminating cavitation, it has been shown that it is not possible to achieve this desirable situation in all practical cases. Thus the resistance of propeller materials is of some importance.

Despite what has been said above in the context of the mechanism of cavitation erosion, it is not found adequate to assume that resistance will be directly related to normal fatigue or corrosion fatigue performance as determined by the usual methods. Many investigators have attempted to relate erosion behaviour to some material property but with only limited success. It is necessary then and perhaps desirable anyway, to evaluate materials by some direct means.

Of the several experimental methods available, S.M.M. has selected the technique based on an ultrasonic vibrator. Briefly, a specimen of material under test is vibrated in a vertical plane whilst immersed in the test liquid, which is usually sodium chloride solution. Although the amplitude of this movement is small, 0.03mm, the frequency (20kHz) is such that the local pressure drop under the rising specimen is sufficient to cause cavitation, The descending portion of the cycle stimulates implosion of the cavities, releasing energy in the form of noise and a shock wave which strikes the specimen test surface. In this way, cavitation conditions of a specified and fixed intensity can be used to examine rates of erosion for almost any material.

It is not the purpose of such testing to prognosticate the rates of erosion on propellers in service, but to evaluate materials on a relative basis to enable any alloy's performance to be compared with those of propeller materials which have been in varied service for many years.

Results from these tests confirm the high resistance to erosion shown by modern, high strength copper-base alloys and indicate that they can be expected to perform better than, for instance, the stainless steels used for propellers so far. Indeed the best copper alloys show a resistance to cavitation erosion similar to some titanium alloys, and are only inferior to materials which are unlikely to find application as marine propellers. Coatings, in general, do not show much promise of being useful in reducing cavitation erosion. In particular, the epoxy resins used as protective coatings offer little resistance to attack and therefore should only be considered for the repair of erosion damage if the source of cavitation has been corrected or as a temporary expedient.

It is recommended to the reader that if more information about the alloys is required then it is available on the company's website.