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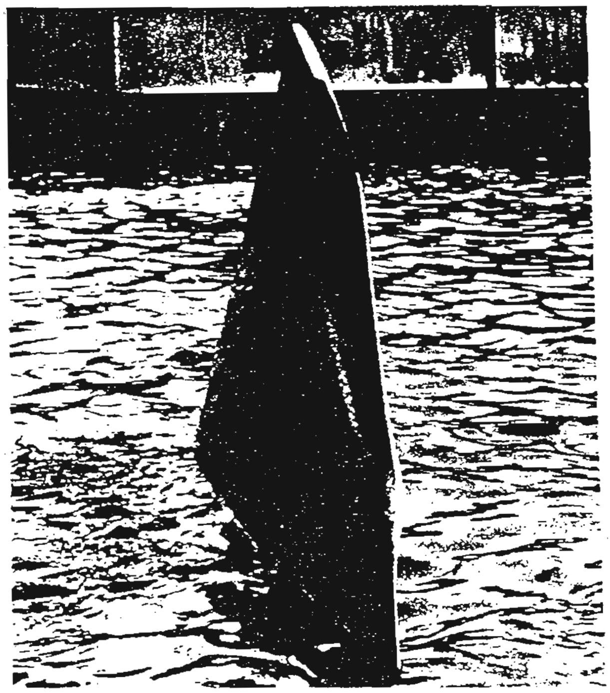

Fig. 44 Bent trailing edge of propeller blade caused by cavitation

multaneous collapse. This explains the bending of trailing edges towards the pressure side. For the prevention of this form of cavitation damage, a good compromise between the camber distribution of the blade section and the angle of attack at which the blade section works is necessary.

(*c*) *Cavitation-induced vibrations and noise.* Ship vibrations are determined by the response characteristics of the ship structure and by the excitation level. Propeller-induced vibratory forces on the afterbody of a ship form the largest part of these excitation forces. This aspect of the influence of cavitation has been the subject of significant experimental studies. It was found that cavitation considerably influences the whole problem of ship-propeller interaction. Cavitation was found both to influence propeller blade stresses and to modify the flow ahead of the propeller. The largest effect, however, was found in the pressure fluctuations induced on the ship's afterbody. Not only the amplitude but also the phase angle of the propeller-induced fluctuating pressures are affected. Propeller cavitation increases the amplitude of these vibratory pressures, depending on blade number and extent of cavitation, with a factor between 1 and 10 and sometimes even higher. This is primarily due to the variation in angle of attack of the flow causing large variations in the size of the cavities on the blades thereby causing large volume variations. When the cavities on the propeller blade do not fluctuate as much, such as occurs in a uniform flow, the pressure fluctuations on a nearby body are not increased as much; see Chapter VII.

Cavitation not only influences low frequency propeller-induced pressure fluctuations on the ship hull but also increases high frequency noise levels in ships. For warships this aspect is particularly disturbing. The increase of underwater self-noise with increasing cavitation (i.e., with increasing ship speed) reduces the ship's sonar-detection capabilities considerably. It is therefore important for a warship to have propellers with a maximum cavitation-free speed range. A high cavitation inception ship speed is nowadays considered to be essential in design of naval propellers.

7.7 Criteria for Prevention of Cavitation. Many criteria have been proposed for predicting the onset of cavitation. The earliest ones, using the average thrust per unit area of projected blade surface, are today not sufficient in many sophisticated designs, although still useful as a first guide. The criterion devised by Barnaby from the *Daring* trials was to limit the pressure to 76.7 kN/m^2 (10.8 psi) of projected area for a tip immersion of 0.28 m (11 in.), increasing this limit by 2.5 kN/m^2 (0.35 psi) for every additional 0.305 m (ft) of immersion.

For the same lift coefficient C_L on a section, the maximum reduction in pressure on the back depends on the shape of the section and on the conditions under which it is operating. Any proposed criteria must take account of these factors, and it is difficult to find one which is really satisfactory.

The modern approach is to calculate the pressure distributions around suitable sections, or to measure them in a wind or water tunnel. A knowledge of the real incidence angle obtained from circulation theory can then be used to determine the maximum reduction of pressure on the back of the section for comparison with the static pressure $(p_0 - p_V)$ available. The true angle of incidence depends on the wake pattern in which the propeller is working, and such calculations have to be made using the average circumferential wake at each particular radius. In practice the angle of incidence will vary both above and below the average, so that cavitation will occur at somewhat lower revolutions, and allowance must be made for this fact. By the same token, cavitation will be delayed or avoided by making the wake more even by attending to shape of hull, clearances, propeller rake and the alignment of bossings or shafts and struts with the average flow direction.

Many propellers are still designed from charts derived from methodical series tests, and in designing by the circulation theory it is necessary to begin with some chosen propeller diameter, also determined from a design chart. Some general criterion is therefore needed for the choice of blade area to avoid cavitation. A diagram designed to provide such guidance in order to avoid excessive cavitation and erosion under average service conditions at sea was given by Burrill (1943). He used a coefficient τ_c expressing the mean thrust loading on the blades, defined as

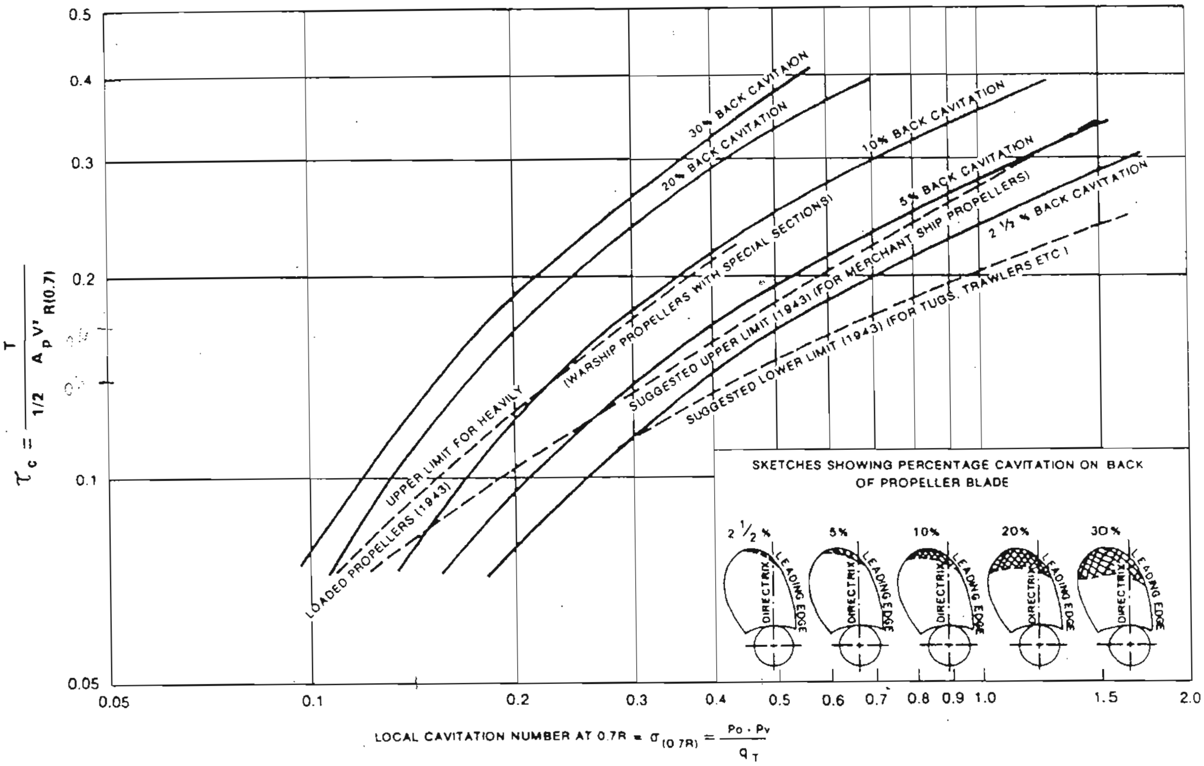

Fig. 45 Simple cavitation diagram (Burrill, et al, 1943, 1962-63)

$$\tau_c = \frac{T/A_P}{\frac{1}{2}\rho(V_R)^2}$$

plotted to a base of $\sigma_{0.7R}$, where

T is thrust in kN
A_p is projected blade area in m^2
V_R is relative velocity of water at 0.7 radius in m/sec.
$\sigma_{0.7R}$ is local cavitation number at 0.7 radius
ρ is mass density, kg/L.

The projected blade area A_P can be found from the more usual developed area A_D by using Taylor's approximate formula

$$A_P/A_D = 1.067 - 0.229 \times \text{pitch ratio} \quad (59)$$

The thrust can be calculated from P_E or P_D from the expressions

$$T = \frac{P_E}{(1 - t)V}$$

or

$$T = \frac{P_D\,\eta_D}{(1 - t)V}$$

The cavitation number $\sigma_{0.7R}$ is calculated using the relative velocity V_R at 0.7 radius and the pressure at the centerline of the propeller, viz.

$$\sigma_{0.7R} = \frac{p_0 - p_V + \rho g h}{\frac{1}{2}\rho(V_A 2 + (0.7\pi n \mathrm{D})^2} \quad (60)$$

an approximate formula for which is

$$\sigma_{0.7R} = \frac{188.2 + 19.62\,h}{V_A\,2 + 4.836 n^2 D^2} \quad (61)$$

where $(p_0 - p_V)$ is pressure at screw center line in N per m^2, h is head of water at screw center line, m

The chart, reproduced in Fig. 45, was based originally on experience with full-sized propellers and gave lines for suggested upper limits of T/A_P for heavily loaded (warship) propellers with special sections and for merchant ship propellers in order to avoid serious back cavitation. A third line indicated the lower limits of T/A_P to avoid face cavitation on tugs and trawlers. Systematic tests of a series of model propellers with circular back sections in the cavitation tunnel at King's College, Newcastle, confirmed in a general way that the model results were in reasonable agreement with the practical experience on which the chart was based (Gawn, et al, 1957). Later a series of four-bladed merchant ship propeller models was run in the same tunnel covering a range of pitch ratio and values of σ (Burrill, et al, 1962–63.) From these tests lines were added to the diagram, Fig. 45 indicating 2½, 10 and 30 percent back cavitation. It will be seen that the line for 5 percent back cavitation lies very near that given originally for merchant ships. The authors state that observations on many other propellers in the tunnel running at the average service condition have shown cavitation of this kind and extent, and have been found reasonably free from erosion after several years in service. They therefore concluded that the line indicating 5 percent back cavitation was a suitable criterion at which to aim in practical design calculations, and that "even recent experience with propellers of modern design would not suggest any material alteration in the positioning of this upper limiting line for aerofoil type propellers."

A useful formula for obtaining a first indication as to the required expanded blade area ratio was derived by Keller (1966),

$$\frac{A_E}{A_o} = \frac{(1.3 + 0.3Z)T}{(p_o - p_v)\,D^2} + k \qquad (62)$$

where:

T is thrust in N (or kN)
Z is number of propeller blades
$p_o - p_v$ is pressure at centerline of propeller in N per m^2 (or kN per m^2)
k is a constant varying from 0 (for transom-stern naval vessels) to 0.20 (for high-powered single-screw vessels).

The subject of cavitation criteria in propeller design can really only be dealt with adequately by incorporating pressure distribution, angle-of-attack, and cavitation number information into a detailed design process, for every radius. Criteria such as the Burrill chart and the Keller formula do not reflect the influence of the wake or propeller blade geometry such as pitch, camber and thickness distribution. They should therefore be used with care.

Section 8

Propeller Design

8.1 Methods of Propeller Design. The design of a e propeller is almost invariably carried out by one of two methods, although each method covers a number of procedures differing in detail.

In the first of these, the design is based upon charts giving the results of open-water tests on a series of model propellers. These cover variations in a number of the design parameters such as pitch ratio, blade area, number of blades, and section shapes. A propeller that conforms with the characteristics of any particular series can be rapidly designed and drawn to suit the required ship conditions.

The second method is used in cases where a propeller is heavily loaded and liable to cavitation, or has to work in a very uneven wake pattern, when it is desirable to carry out a detailed design using circulation theory. Basically this involves finding the chord width, section shape, pitch, and efficiency at a number of radii to suit the average circumferential wake values and give optimum efficiency and protection from cavitation. By integration of the resulting thrust and torque-loading curves over the blades, the thrust, torque, and efficiency for the whole propeller can be found. Before such detailed design can be started it is necessary to know preliminary dimensions and in general these are found from standard charts.

Also some choices as to the propeller characteristics have to be made such as number of blades, skew, etc. The next sub-section gives a general philosophy on ller design with respect to these choices. After that two methods of design will be presented, one based on systematic series and another one based on theoretical calculations.

8.2 General Propeller Design Philosophy. Continuing with a qualitative discussion of the considerations that may influence the propeller design (Cumming, et al, 1974), a detailed account of an actual propeller design and its evaluation by calculations and model tests has been given by Boswell, et al (1973) concerning a highly skewed propeller.

(*a*) *Diameter*. The maximum diameter is usually limited by the geometry of the aperture although sometimes tunnels may be applied to allow larger propellers. Another limiting factor is imposed by propeller induced unsteady hull forces which decrease with increasing clearance. The propeller efficiency usually increases with increasing diameter. A larger diameter will change the radial distribution of the wake in which the propeller operates, however, which can lead to serious detrimental effects if the blades extend into a region of greater flow non-uniformity. Also, keeping the rate of revolution constant, a larger diameter will lead to higher tip velocities and hence to a reduced cavitation index. The latter effect usually more or less balances the delay of tip vortex cavitation caused by the smaller gradient of the bound circulation. This gradient is smaller since the same thrust load is spread over a larger distance. Finally, the hull efficiency may be reduced by applying a larger diameter.

As can be seen from the above discussion the choice of the diameter will be a compromise. Also, changing the diameter will lead to changes in other parameters. Therefore this discussion is necessarily qualitative. The final choice of all parameters involved will be interrelated with the speed to be attained and by the