6. CAVITATION

a) The Basics of Cavitation

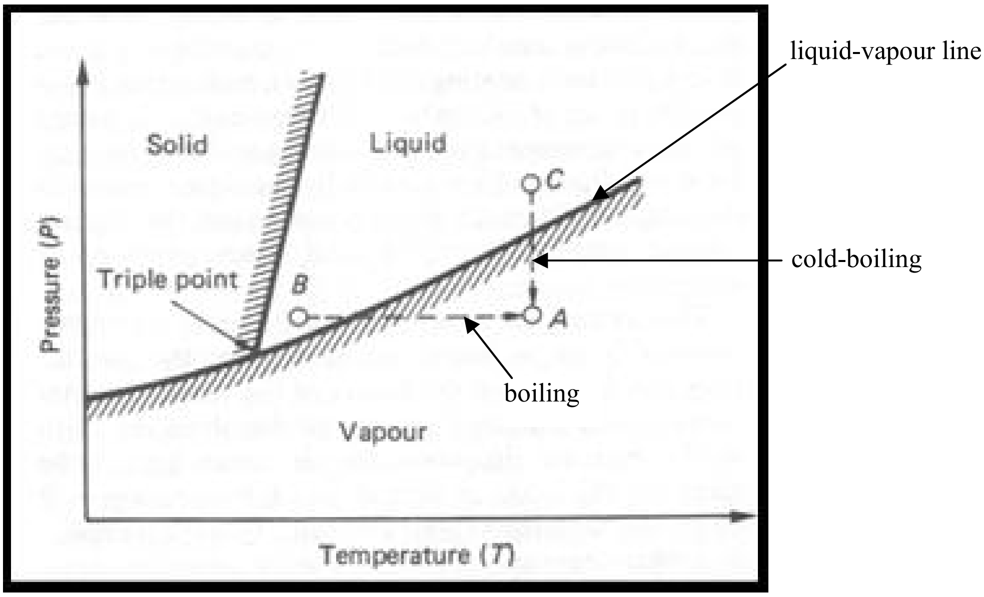
i- Physics of cavitation

Cavitation is a general fluid mechanics phenomenon which can occur whenever a liquid used in a machine inducing pressure and velocity fluctuations in the fluid (e.g. Pumps, turbines, propellers, bearings, even the heart and knee joints).

When cavitation occurs the liquid changes its phase from liquid into vapour at certain flow region where local pressure is very low due to the high local velocities (e.g. propeller tips).

There are two types of vaporization:

1. The first is the well-known process of vaporization by increasing temperature (boiling)
2. Vaporization under nearly constant temperature due to reduced pressure (i.e. cold boiling) as in the case of cavitation.

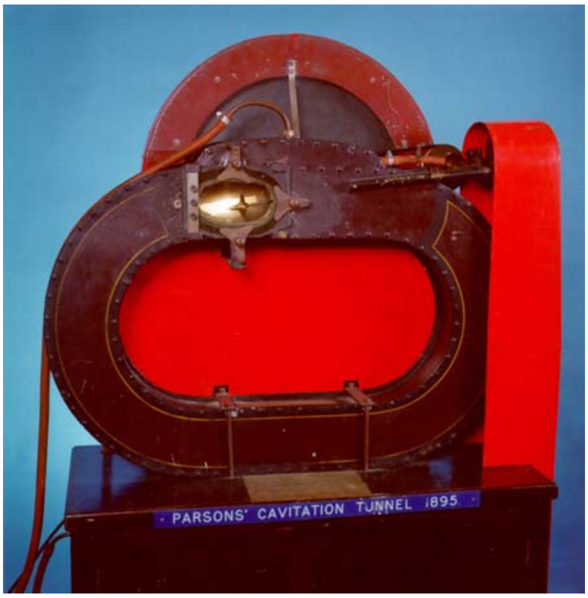


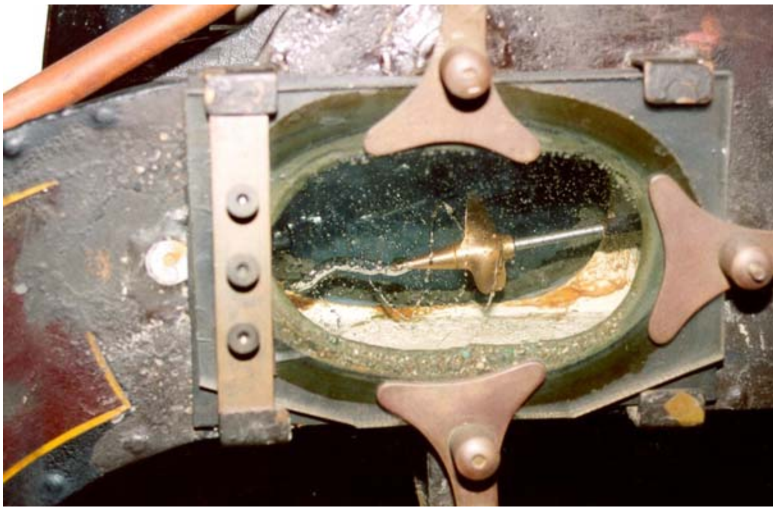
The cold boiling process and hence cavitation depends on the purity of water. If water contains a significant amount of dissolved air, then as the pressure decreases the air comes out of the solution and forms cavities in which the pressure will be greater than the "*vapour pressure*". This effect applies also when there are no visible bubbles. Submicroscopic gas bubbles can provide suitable nuclei for cavitation purposes. Hence cavitation can either be "*vaporous*" or "*gaseous*" perhaps, a combination of *both*.

When cavities are formed in fluid, this violates the homogeneous character of the liquid resulting in practical problems

ii- Historical development

- Euler (Swiss Mathematician) first reported the possibility of cavitation on a particular design of water wheel in 1754.
- Reynolds wrote series of papers on engine-racing in screw propelled steamer and introduced cavitation as we know it today (INA, 1873).
- Barnaby reported over speeding characteristics of 27 knots Torpedo boat destroyer HMS Daring in its trials in 1893.
- Parsons built the world's first cavitation tunnel to observe the phenomena in model scale and tested the propellers of his famous world's first steam turbine boat "Turbinia" in 1895. This small tunnel is still kept in working order at the City Museum in Newcastle upon Tyne, UK. Parsons also constructed a larger tunnel 15 years later in which he could test 12" diameter propeller models.





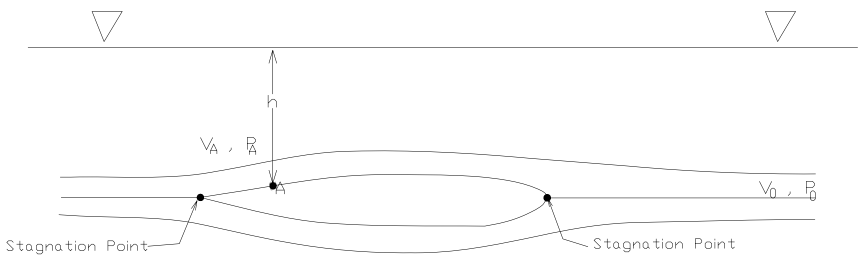
Larger tunnels were constructed in Europe and America during the 1920's and 1930's.

iii- Cavitation inception

The process of beginning of cavitation is called "Cavitation Inception". Pure water can withstand considerable low pressure (i.e. negative tension) without undergoing cavitation. A necessary condition for the inception is the presence of weak spots in the water which break the bond between the water molecules. These weak spots are generally tiny gas bubbles called "nuclei". The presence of nuclei in water depends on circumstances.

In sea water there are nuclei of all sizes. For the cavitation inception "*the inception pressure*" is assumed to be equal to the vapour pressure at the sea. However at model scale, a lack of nuclei is common and "*the inception pressure*" will be lower than the vapour pressure. This is a major cause of *Scale Effects* at model scale.

Consider a pressure at an arbitrary point "A" of a 2D profile section subjected to a uniform flow.



By definition cavitation inception" at point "A" is:

$$P_A \le P_V$$
$$or$$
$$\frac{P_0 - P_A}{\frac{1}{2}\rho V^2} \ge \frac{P_0 - P_V}{\frac{1}{2}\rho V^2} \qquad (1)$$

where P_0 and V are the undisturbed fluid pressure and undisturbed flow velocity, respectively. P_A and V_A are the local flow pressure and velocity at point A.

Along the streamline if we write Bernoulli Equation:

$$P_0 + \frac{1}{2}\rho V^2 = P_A + \frac{1}{2}\rho V_A^2$$
$$P_0 - P_A = \frac{1}{2}\rho (V_A^2 - V^2) \qquad (2)$$

By substituting Eq. (2) into (1)

$$\frac{P_0 - P_A}{\frac{1}{2}\rho V^2} = \frac{\frac{1}{2}\rho(V_A^2 - V^2)}{\frac{1}{2}\rho V^2} = \frac{\Delta P}{q} \geq \frac{P_0 - P_V}{\frac{1}{2}\rho V^2} \tag{3}$$

σ is the cavitation number and C_P is the non-dimensional pressure coefficient, they are defined as

$$\sigma = \frac{P_0 - P_V}{\frac{1}{2}\rho V^2}$$

and (4)

$$C_P = -\frac{\Delta \mathrm{P}}{\mathrm{q}}$$

In Eq. (3) P_0 is the sum of static pressure head P_h and atmospheric pressure P_a, i.e.

$$\sigma = \frac{P_0 - P_V}{\frac{1}{2}\rho V^2} = \frac{P_a + P_h - P_V}{\frac{1}{2}\rho V^2}$$

with $\mathrm{P_h} = \rho g h$ (5)

and

$$\frac{\Delta \mathrm{P}}{\mathrm{q}} \geq \sigma \text{ or } \sigma \leq \frac{\Delta \mathrm{P}}{\mathrm{q}}$$

According to Eq. (5) σ is constant. Therefore we can set up a simple criterion for cavitation based upon the cavitation number σ and pressure distribution C_P

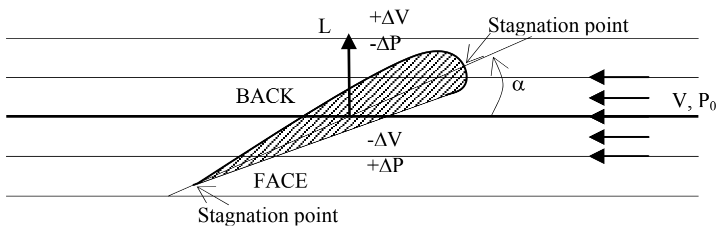
If $\sigma \leq \frac{\Delta P}{q}$ cavitation occurs

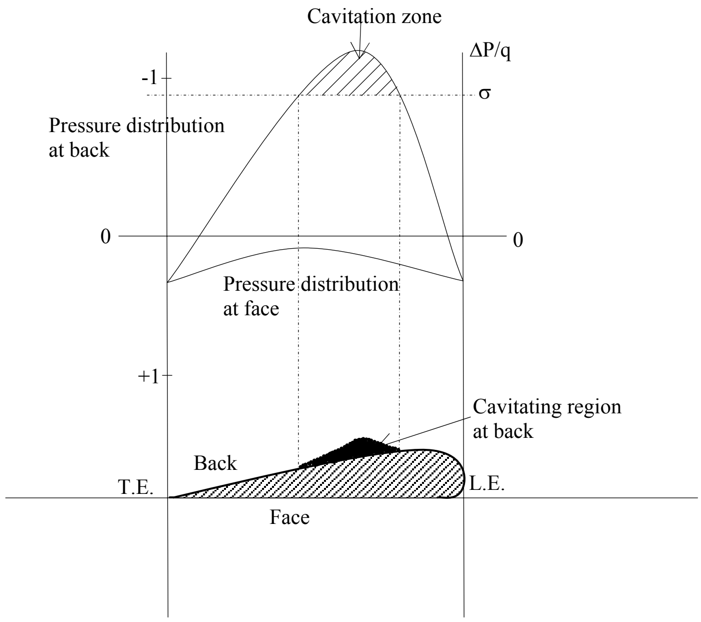
$\sigma > \frac{\Delta P}{q}$ cavitation does not occur

iv- Effect of angle of attack on cavitation

Let us consider a 2D profile and investigate the pressure distribution around it depending upon the angle of attack of the flow (α).

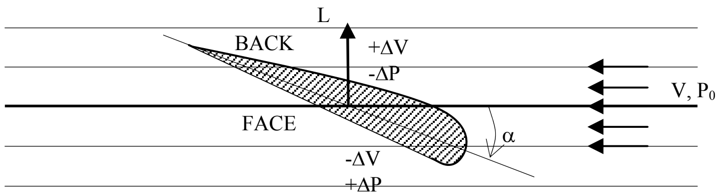
1. Positive angle of attack

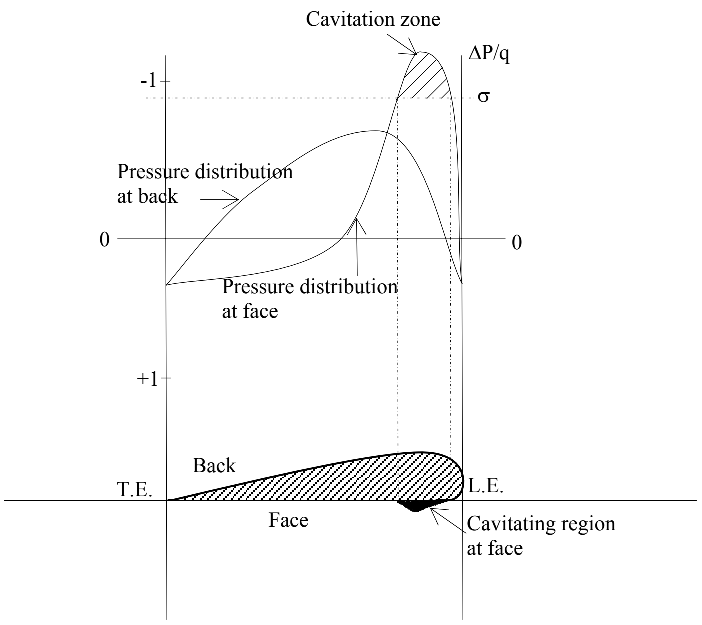




As seen a positive angle of attack may cause cavitation at the back of the profile and towards the trailing edge.

2. Negative angle of attack





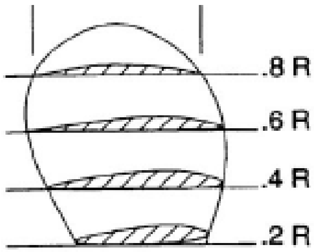
when α<0 cavitation will likely occur at the face of the profile rather than back as in the positive angle of attack case.

3. Zero angle of attack, α ≅ 0

Results in cavitation zone behind the max thickness region of the profile at the back (i.e. towards trailing edge).

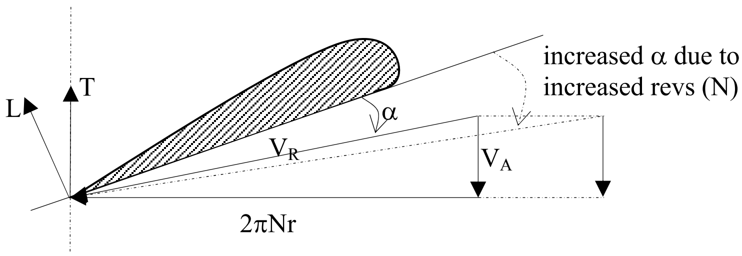
v- Cavitation on a propeller blade

A propeller blade can be assumed to be made up from a number of 2D profiles investigated as it was seen before.

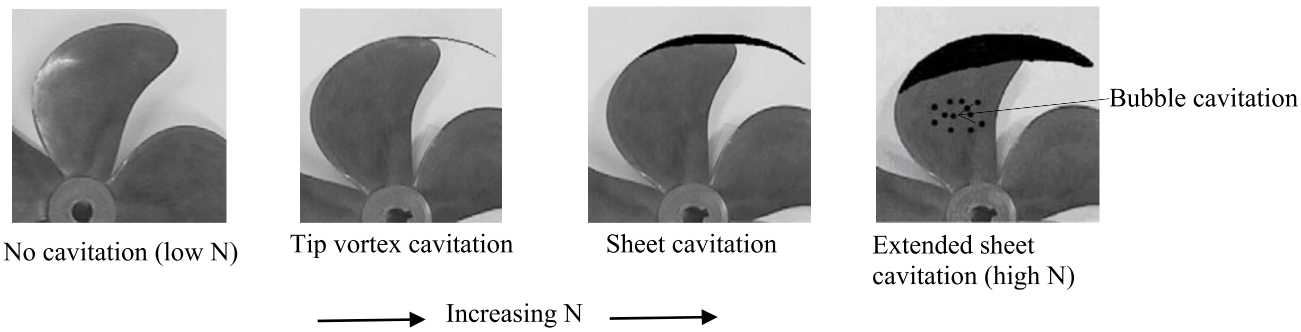


A lift force (L) on each profile is the integration of the pressure (ΔP) along each profile chord. Now by looking at the pressure distribution (i.e. $\Delta P/q$) curve of a profile we can say that there is no relation between the lift (its integration along the blade radius and in the ship's main axis is thrust) and the occurrence of cavitation. What important is the peak values of the negative pressure distribution. When these peak values are greater than the cavitation number (σ) cavitation will occur.

Now let us investigate how changing angle of attack of a propeller blade (α) influences extend and position of cavitation.



As can be seen in the above figure, α can be increased by keeping V_A constant and by increasing rate of rotation (N). This rotational speed effect will result the following cavitation patterns.



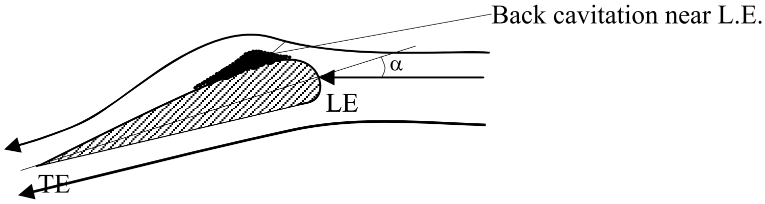
b) Types of Cavitation Experienced by Propellers

In the following we investigate the types of cavitation depending upon;

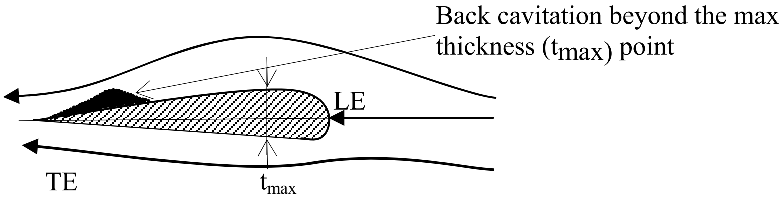
i) Location on the blade of a propeller
ii) Physical appearance

i) Depending upon location on a blade

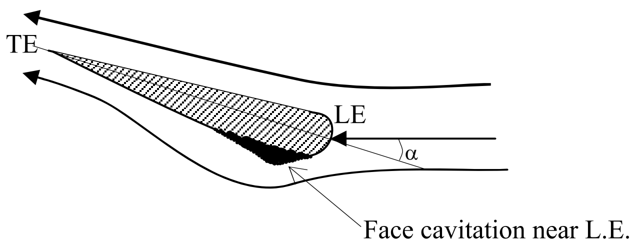
Back cavitation (i.e. $\alpha>0$)



Back cavitation (towards T.E.) (i.e. $\alpha \sim 0$)

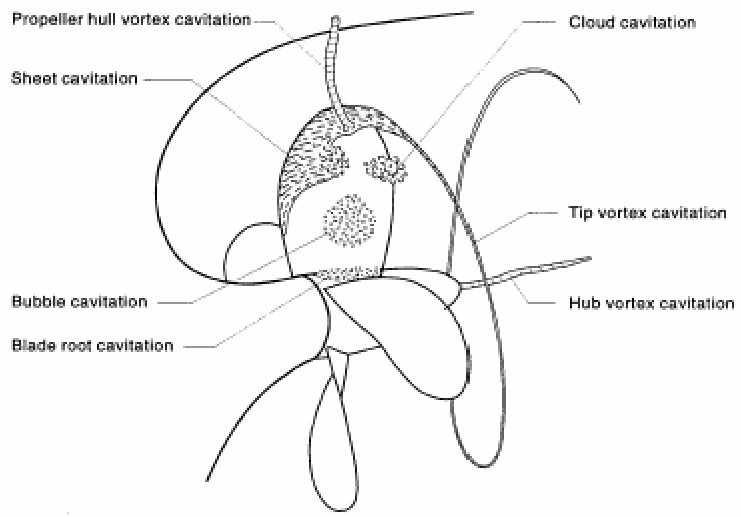


Face cavitation (i.e. $\alpha<0$)



ii) Depending upon physical appearance of cavitation

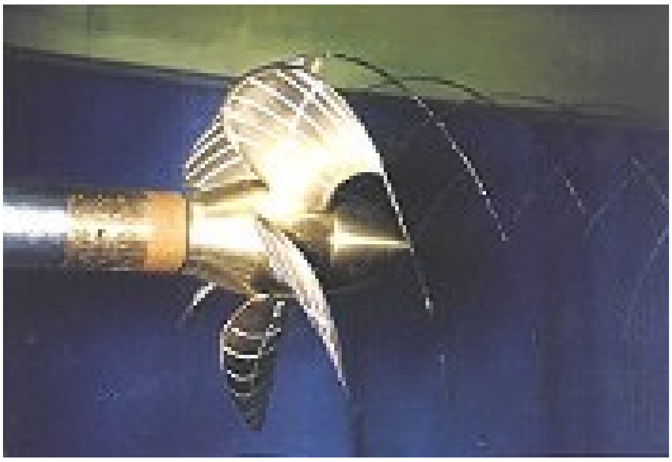
- Tip and Hub vortex cavitation
- Sheet cavitation
- Bubble cavitation
- Root cavitation
- Propeller-Hull vortex cavitation
- Unsteady sheet cavitation (cloud cavitation)



Tip and Hub vortex cavitation

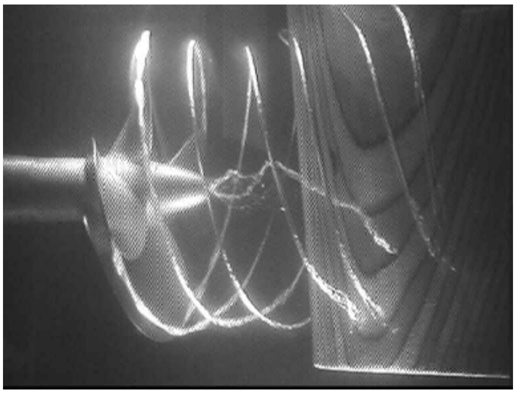
The vortex types of cavitation, with few exceptions, occur at the blade tips and hub of the propeller and they are generated from the core of these vortices where the pressure is very low. When this pressure is lower than the vapour pressure "Vortex" cavitation occurs.

The tip vortex cavitation is normally first observed some distance behind the tips of the propeller blades which is said to be "unattached" but as the vortex becomes stronger, either through higher blade loading or decreasing in σ, it moves towards the blade tip and ultimately becomes attached.



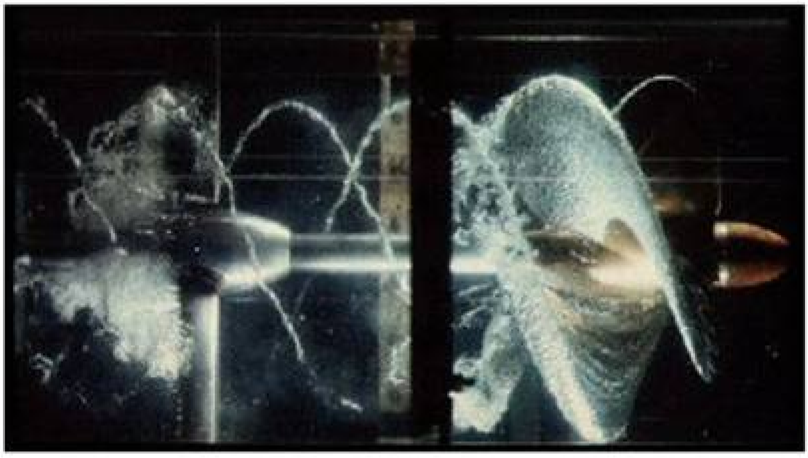
The hub vortex is formed by the combustion of individual vortices shed from each blade root and although individually these vortices are unlikely to cavitate, under the influence of a converging propeller cone the combination of the blade root vortices has a high susceptibility to cavitate.

When this occurs the resulting cavitation is normally very stable appearing like a “rope” with strands corresponding to the number of blades of the propeller. This type of cavitation may also harm the rudders behind the propeller causing erosion on them. It can be avoided using Propeller Boss Cap Fins (PBCF) or other type vanes

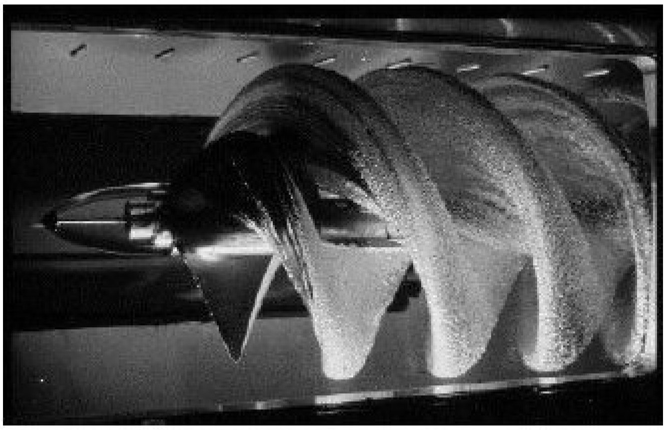


Sheet cavitation

Sheet cavitation occurs when the pressure distribution has a strong adverse pressure gradient and the flow separates from the blade surface. Sheet cavitation initially becomes apparent at the leading edges of the propeller blades on the back when the blade sections are working at positive angle of attack.



Conversely if the sections are operating at negative angle of attack, the sheet cavitation may initially appear on the face of the blade. The sheet cavitation occurs when a leading edge suction peak is lower than the vapour pressure (i.e. $C_p > \sigma$)



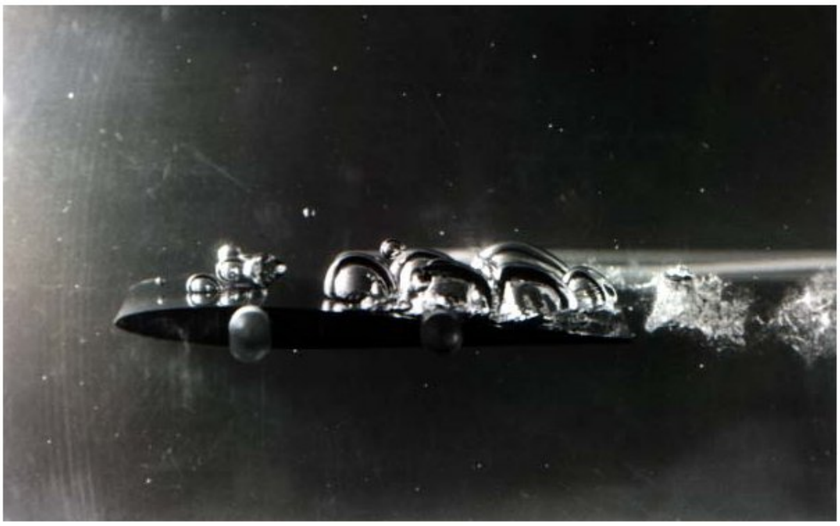
Sheet cavity is generally stable although there are cases where instability may occur. On commercial propeller the sheet cavity gradually merges with the tip vortex.

Bubble Cavitation

Bubble cavitation is primarily affected by the pressure distribution which causes high suction pressure in the mid- chord region of the blade section. Thus the combination of camber line and section thickness plays an important role on the susceptibility of a propeller towards bubble cavitation.

When the blade sections are relatively thick and operate at a small angle of attack the bubble cavitation occur.

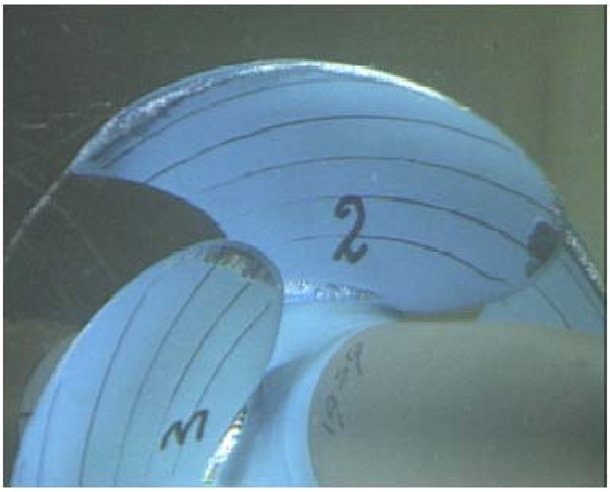
For example near the root of controllable pitch propeller where the chord length is restricted and strength requires thick blade sections.

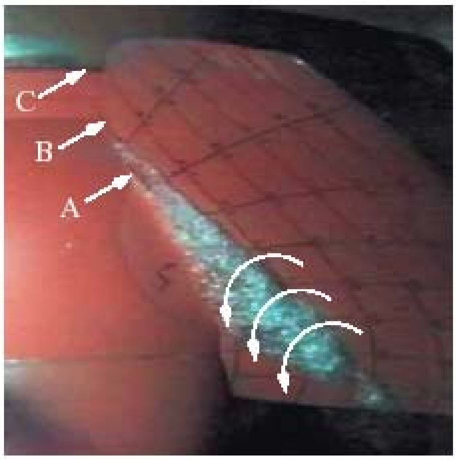


Bubble cavities collapse very violently so that this cavitation is noisy, erosive and bad.

Root Cavitation

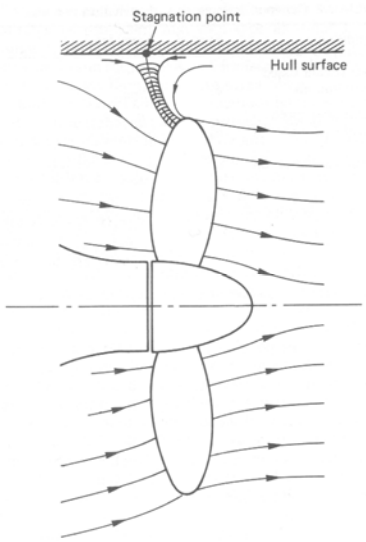
This type of cavitation may occur at the blade root and has the shape of a wedge. The top of the wedge can be at the leading edge, but it can also start on the blade itself. Root cavitation is related to the horse shoe vortex developed at root as well as inclined shaft and wake shadow effect created by the shaft brackets, bossings, etc. It is commonly observed on controllable pitch propellers (CPP).





Propeller-Hull Vortex (PHV) Cavitation

A special form of cavitation reported in early 1970's is the PHV cavitation. This type of cavitation can be described as the "arching" of a cavitating vortex between propeller tip and ship's hull and it is pronounced for small tip clearance of the propeller and hull.



The PHV is considered to form due to turbulence and other flow disturbances close to the hull, causing a rotation about the stagnation point, which is accentuated away from the hull by the small radius of the control volume forming the vortex. The factors leading to the formation of PHV cavitations are suggested

- Low advance coefficient
- Low tip clearance
- Flat hull surfaces above the propellers

Unsteady Sheet (Cloud) Cavitation

Cloud cavitation is frequently found behind strongly developed steady sheet cavities and generally in moderately separated flow in which small vortices from the origins for small cavities. This type of cavitation appears as a mist or “cloud” of very small bubbles and its presence should be taken seriously.

c) Effects of Cavitation on Propellers

Cavitation phenomenon can happen any part of a ship hull where the local pressures are very low. The propeller itself is the greater source of cavitation due to induced high local velocities (or low pressures) around the blades.

When cavitation occurs depending upon its extend and severity, the propeller may suffer from

i) Performance breakdown
ii) Noise
iii) Vibration
iv) Erosion

i- Performance breakdown

Partial cavitation on a propeller blade will not affect its thrust. Indeed a small amount of cavitation may even increase the camber of the blade section and hence increase the thrust. When 20-25% of blade section is covered by cavitation both thrust and torque reduce. Thrust decreases more rapidly than torque and hence efficiency is reduced. On commercial propellers this rarely happens since the propeller loading and the rate of rotation is low.

However, on highly loaded propellers and particularly propellers with high rotational speeds the effect of cavitation will influence the performance characteristics. (e.g. Fast naval ships at full speeds, tugs in towing condition, fast ferries, container ships, etc).

In some propeller design charts this effect is included in K_T, K_Q and η figures as correction.

ii- Noise

Sound is defined as mechanical disturbance, which is propagated in an elastic medium, of such character as to be capable of exciting the sensation of hearing (BSRA, 1982). It is generated whenever there is a relative motion between two fluids or between the fluids and a surface. Whereas noise is described as unwanted sound and interferes with the normal functioning of a system.

The noise generated from a ship system can be grouped into two main categories:

- self noise from all shipboard sources generated by vessel, personnel and equipment
- radiated noise generated by the ship and experienced at some point far away from the ship.

Considerable part of noise generated by the ship system is underwater noise and three major sources of the underwater noise are defined by Ross (1976), which are related to the machinery, propeller and flow noise. Amongst these sources the propeller noise is the most important one and generated by the following mechanisms in water:

1. water displacement by propeller blades
2. pressure difference between suction and pressure sides of the blade
3. sudden collapse of a cavity bubble or vortex
4. the periodic fluctuations of the cavity volumes

By considering the above mechanisms, the first two mechanisms are associated with a propeller in non-cavitating state, the latter two cases are associated with a propeller in cavitating state. Therefore, a typical propeller noise usually has:

- a non-cavitating
- a cavitating part and the associated noise spectrum is heavily influenced by cavitation

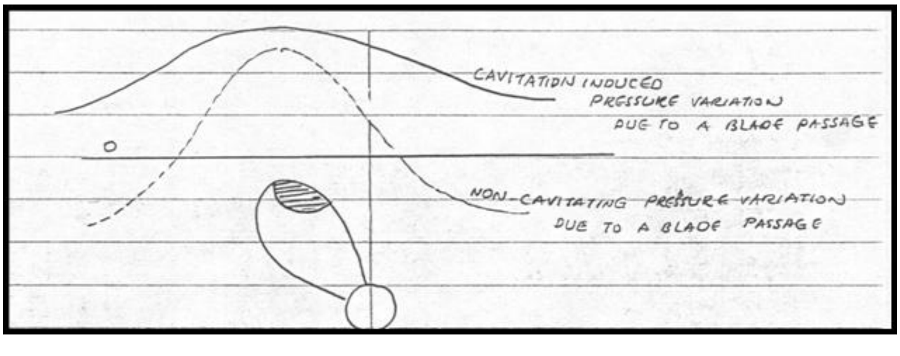
Cavitation noise may be generated by various types of cavitation travelling bubbles, sheet cavitation, tip vortex cavitation, etc.

When the external pressure around a cavitation bubble starts to increase, after a short time, the pressure gradient between the outer and inner pressure will decrease, and then the bubble will enter its collapse stage. The cavitation bubble in the collapse stage creates shock waves hence noise. On the other hand, the inception stage of cavitation also affects the noise level.

iii- Vibration

Sheet cavitation on a blade can have considerable volume. The dynamic behaviour of this large volume of vapour generate strong "pressure fluctuations" at frequencies of the BR (B.R.=kNZ/60 Hz, k=1) and its multiples (k=2, 3,..). These frequencies are lower than the noise frequencies. The pressure fluctuations have very large wave length and hence they are independent of the compressibility of the flow. Therefore the pressure around the propeller and aft end varies in phase with the compressibility of the fluid distinguishes the "Cavitation Induced Pressure Fluctuations" from "Cavitation Induced Noise".

The constant phase of the cavitation induced pressure causes "Hull Vibrations". This is different from the pressure field from the passage of a blade without cavitation, which is felt at different times at different places along the hull.



The figure shows the pressure disturbance at certain time and blade position. The pressure due to cavitating blade reaches its max and min everywhere on the hull at the same time (in phase) while the pressure due to non-cavitating blade moves over the hull surface with the moving blade.

Unacceptable hull vibrations can be reduced by

- Re-designing the aft end and propeller
- Changing the response (i.e. natural frequency) of the aft end construction

The latter is only effective when the vibrations are local. The most effective way to avoid vibrations is to make the wake as uniform as possible modifying the aft end. The re-designing of propeller to reduce the cavitation effect involves;

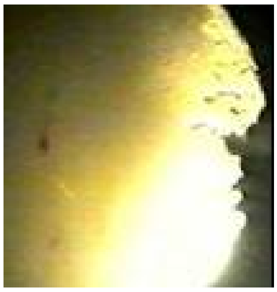
- Increasing blade surface area, particularly at tip.
- Increasing blade “skew”
- Reducing pitch towards the tip i.e. “tip unloading”

iv- Erosion

Generation of a vapour bubble in fluid is a very rapid process. When the bubble moves into a lower pressure zone in the fluid, it will expand rapidly while the pressure inside remains very close to the vapour pressure. When this vapour filled cavity encounters a high pressure zone in the fluid (e.g. due to varying wake field), the bubble decreases in size while the pressure inside remains the same

After certain period the bubble becomes very small and surface tension becomes large resulting in collapse cavity. When this occurs close to the blade surface the surface may be damaged and this is known to be “Erosion” which is a mechanical damage. Mechanism for erosion can be due to;

- Micro jet effect
- Shock wave
- Rebounding of bubble cavities
- Collapse of cloud of small bubbles.

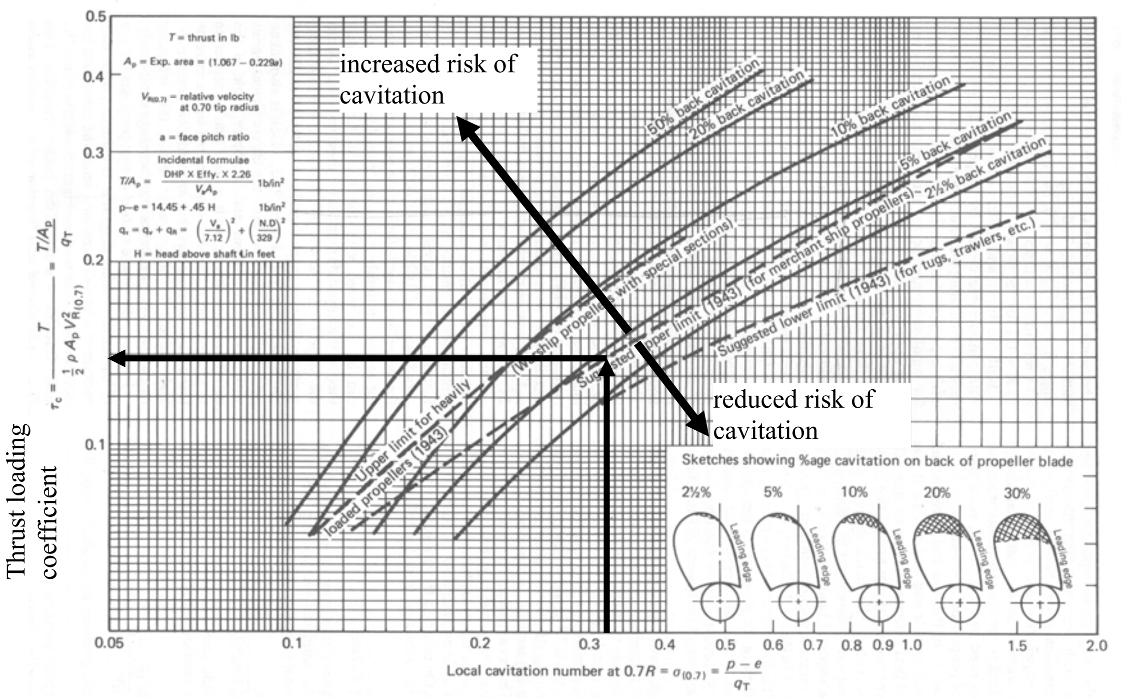
d) Cavitation Considerations in Design (to Minimise Risk of Cavitation)

From the early works of Parsons and Barnaby and Thornycroft on both models and full scale it was concluded that extreme back or face cavitation causing thrust breakdown could be avoided by increasing the blade surface area. Criteria were subsequently developed by relating the “Mean Thrust” to the required “Blade Surface Area in the form of a limiting thrust loading coefficient.

Two of the best known criteria are those derived by BURRILL and KELLER.

i- Burrill’s method

It was proposed for fixed pitch, conventional propellers by Burril.

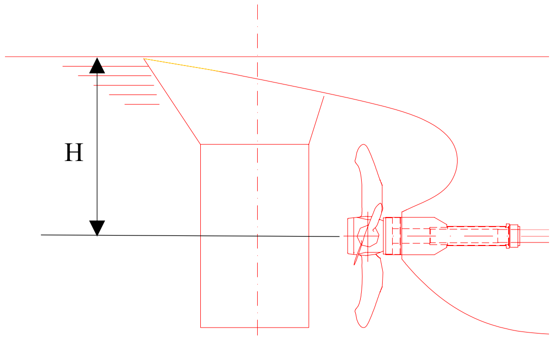


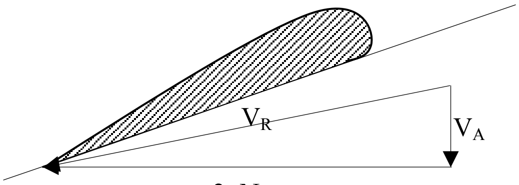
On the diagram

τ_C is the thrust loading coefficient and defined as $\tau_C = \dfrac{T / A_P}{q_T}$

where T is thrust, A_P is propeller projected area and q_T is dynamic pressure at r=0.7R and defined as:

$$q_T = \frac{1}{2}\rho V_R^2$$





V_R is the resultant velocity at r=0.7R and defined as:

$$V_R = \sqrt{V_A^2 + (2\pi N(0.7R))^2}$$

Cavitation number σ_R is defined as:

$$\sigma_R = \frac{P_0 - e}{q_T}$$

where P_0 is the static pressure at the shaft centerline, e is saturated vapour pressure (i.e. P_V)

In using Burril's diagram:

σ_R is calculated and the value of τ_C is read off at the σ_R from the diagram and the projected area for the propeller can be calculated. To derive the expanded area from the projected area, Burrill provided the empirical relationship which is valid for conventional propeller forms as:

$$A_E \cong \frac{A_P}{(1.067 - 0.229\frac{P}{D})}$$

where $A_E \approx A_D$ assumed.

Expanded blade area ratio - EAR

$$\frac{A_E}{A_0} = \frac{A_E}{\frac{\pi D^4}{4}}$$

This calculated area from Burril's diagram is the minimum blade area to avoid cavitation.

ii- Keller's method

The alternative blade area estimation is the Keller Formula as

$$\frac{A_E}{A_0} = \frac{(1.3 + 0.3Z)T}{(P_0 - P_V)D^2} + K$$

where P_0 is the static pressure at the shaft C_L in Pa
P_V is the vapour pressure in Pa (~1700 N/m^2)
T is the propeller thrust (N)
Z is the number of blades
D is the propeller diameter in meters

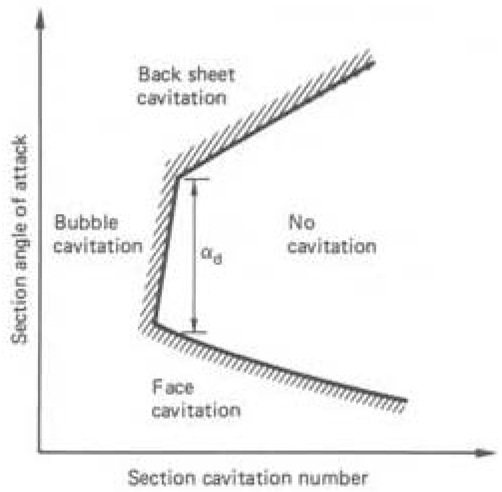
The value of K varies with the number of propellers and ship types as:

K=0.2	for single screws	
K=0.0	for fast naval ships	}Twin screws
K=0.1	for slow merchant ships	

Both the Burrill and Keller criteria have been used with considerable success by propeller designers for estimating the blade area. In many cases, particularly for small ships and boats, these methods and even more approximate ones perhaps form the major part of the cavitation analysis. However for larger vessels and those for which measured model wake field data is available, the cavitation analysis should proceed considerably further to the evaluation of the pressure distribution around the blade sections and their tendency towards cavitation inception and extent.

Cavitation Bucket Diagrams

For propeller blade section design purposes the use of "cavitation bucket diagrams" is valuable, since they represent the cavitation behaviour of a blade section in a two-dimensional sense. The following figure shows the basic feature of a cavitation bucket diagram. This diagram is plotted as a function of section angle of attack (α) versus section cavitation number (σ). However several versions of the diagrams have been produced: typically (α) can be replaced by lift coefficient (C_L) and (σ) by minimum pressure coefficient (C_P).



From the diagram, no matter what its basis, four primary areas can be identified;

1. Cavitation free area inside the bucket
2. Back sheet outside the bucket
3. Bubble cavitation outside the bucket
4. Face cavitation outside the bucket

The width of the bucket (α_d) is a measure of the tolerance of the section to cavitation free operations. Whilst useful for design purposes the bucket diagram is based on 2D flow characteristics and can be therefore give misleading results in areas of strong 3D flow; for example near the blade tip and root.

e) Preventing Cavitation

Several actions can be taken to reduce the likelihood of cavitation occurring:

Fouling: The propeller must be kept unfouled by marine organisms and free of nicks and scratches. Fouling causes a reduction in propeller efficiency as well as the increased chance for cavitation. Even a small scratch can cause significant spot cavitation and result in an increase in radiated noise as well as erosion of the blades. Regular underwater inspections and cleaning of propellers should be carried out to prevent the effects of fouling.

Speed: Every ship has a cavitation inception speed, a speed where tip cavitation begins to form. Unless operationally necessary, ships should be operated at speeds below cavitation inception.

Thrust: For ships shaft speed and thrust must not be increased too quickly when accelerating the ship. An analysis of the equation for the thrust coefficient (C_T) reveals that high propeller thrust (T) and low speed through the propeller (V_A) increases the thrust loading coefficient which may result in cavitation.

Pitch: Operators of ships with controllable pitch propellers must take care that propeller pitch is increased or decreased in a smooth manner. This is usually done as part of the ship's propulsion control system. Incorrect operation of the pitch control system may cause high thrust loading on the propeller blades and increase the likelihood of cavitation.

Depth: Since cavitation is a function of hydrostatic pressure, increasing hydrostatic pressure (i.e. depth) will reduce the likelihood of cavitation. Submarines are uniquely susceptible to depth effects and cavitation as the depth of the submarine affects hydrostatic pressure at the propeller blades. When operating at shallow depth, hydrostatic pressure is decreased and the propeller cavitates at lower shaft rpm and low thrust loading. As a submarines depth increases, hydrostatic pressure increases and cavitation inception is delayed. Therefore, a submarine can operate at higher speeds at deeper depths with little worry about cavitation