Advanced Propulsion System
GEM 423E

Week 4: Cavitation

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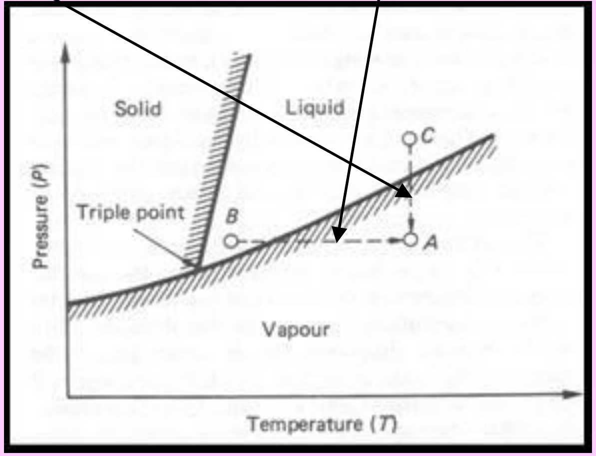
Physics

Physics

- Cavitation is a general fluid mechanics phenomenon which can occur whenever a liquid used in a machine which induces pressure and velocity fluctuations in the fluid (e.g. Pumps, turbines, propellers, bearings,..)
- When cavitation occurs the liquid changes its phase into vapor at certain flow region where local pressure is very low due to the high local velocities

- There are two types of vaporization:
  - Vaporization by increasing temperature (boiling)
  - Vaporization under nearly constant temperature due to reduced pressure (i.e. cold boiling)
  - 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 then the "*vapor 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.

Historical Development

Historical Development

- ***Euler*** (Swiss Mathematician) first reported the possibility of cavitation on a particular design of water wheel in 1754.
- ***Reynolds O.,*** wrote series of papers on engine-racing in screw propelled steamer and introduced cavitation as we know it today.

- ***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 phonemena in model scale and tested the propellers of his famous world’s first steam turbine boat “Turbinia” in 1895.

Sir Charles Parsons, K.C.B

This small tunnel is still kept in working order at the Marine Technology Dept. of Newcastle Univ.

Parsons also constructed a larger tunnel 15 years later in which he could test 12” diameter propeller model

Turbinia on her sea trials

Figure 3. Parsons first cavitation tunnel (1895)

Figure 4. Parsons larger cavitation tunnel (1910)

Where does cavitation occurs?

Where does cavitation occurs

- This phenomenon is more likely to occur under the following conditions.
  - ***The pitch ratio is great:*** If the pitch is small, the propeller more nearly approaches the condition of a disc rotating in the water, which would be the case were the pitch ratio is zero. In this case, there would be no tendency to create a vacuum back of the blades and consequently no boiling. As the pitch is increased, this tendency to create the vacuum back of the blade grows greater with the allied tendency to boil.

- ***<u>The slip is great:</u>*** If there were no slip, the effect would be the same as that of a disc revolving in the water, as in the case of zero pitch; therefore, this tendency towards a vacuum and consequently boiling.
- ***<u>The hub depth is small:</u>*** The deeper the hub, the greater will be the pressure of water on the propeller and, consequently, the less tendency towards a vacuum and consequent boiling.
- ***<u>The blade area is small</u>**<u>:</u>* The smaller the blade area, the greater will be the unit pressure of water on the driving face and this greater tendency to cause on the back of the blade.

Cavitation Inception

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 vapor pressure at the sea.
- However at model scale, a lack of nuclei is common and “*the inception pressure*” will be lower than the vapor pressure.

- This is a major cause of ***<u>SCALE EFFECTS</u>*** 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

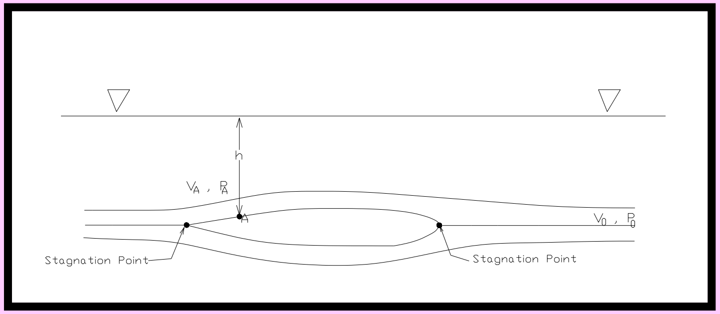
$$\boxed{\begin{array}{l} P_A = P_V \\ \dfrac{P_0 - P_A}{\frac{1}{2}\rho V_0^2} = \dfrac{P_0 - P_V}{\frac{1}{2}\rho V_0^2} \end{array}}$$

- P_0, V_0: Undisturbed fluid pressure and velocity
- P_A, V_A: Local flow pressure and velocity at point “A”

- Along the streamline if we write Bernoulli Equation:

$$P_0 + \frac{1}{2}\rho V_0^2 = P_A + \frac{1}{2}\rho V_A^2 \qquad (1)$$

$$P_0 - P_A = \frac{1}{2}\rho\left(V_A^2 - V_0^2\right) \qquad (2)$$



- By substituting (1) into (2)

$$\frac{P_0 - P_V}{\frac{1}{2}\rho V_0^2} = \frac{\frac{1}{2}\rho\left(V_A^2 - V_0^2\right)}{\frac{1}{2}\rho V_0^2}$$

$$\sigma = \frac{\Delta P}{q} = C_P$$

σ:Cavitation Number

$C_P = \frac{\Delta P}{q}$:Nondimensional Presssure Coefficient

$$\sigma = \frac{P_0 - P_V}{\frac{1}{2}\rho V_0^2} \qquad (3)$$

$$C_P = \frac{\Delta P}{q} = \frac{\frac{1}{2}\rho\left(V_A^2 - V_0^2\right)}{\frac{1}{2}\rho V_0^2}$$

- In equation (3), P_0 ,s the sum of static pressure head P_h and athmospheric pressure P_a *i.e.*

$$\sigma = \frac{P_a + P_h - P_V}{\frac{1}{2}\rho V_0^2} \qquad (4)$$

$$P_h = \rho g h$$

- According to equation (4) “σ” is constant.
- Therefore we can set up a simple criteria for cavitation based upon the cavitation number “σ” and pressure distribution

$$C_P \leq -\frac{\Delta P}{q} \qquad \text{Cavitation occurs}$$

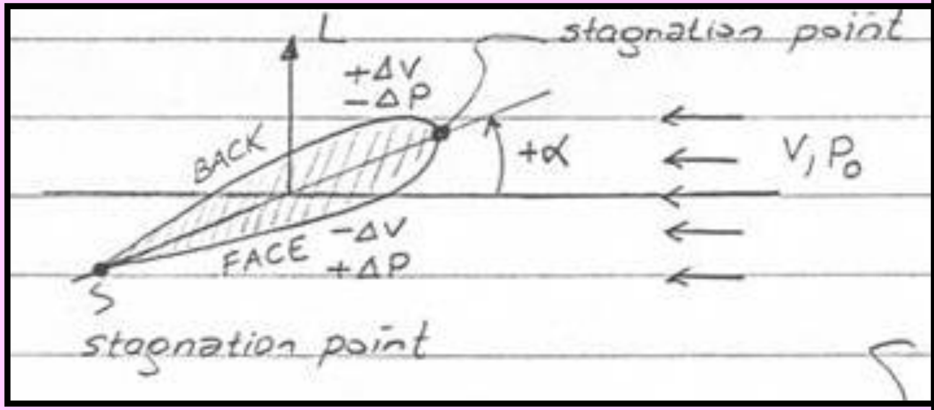
$$C_P > -\frac{\Delta P}{q} \qquad \text{"} \qquad \text{does not occur}$$

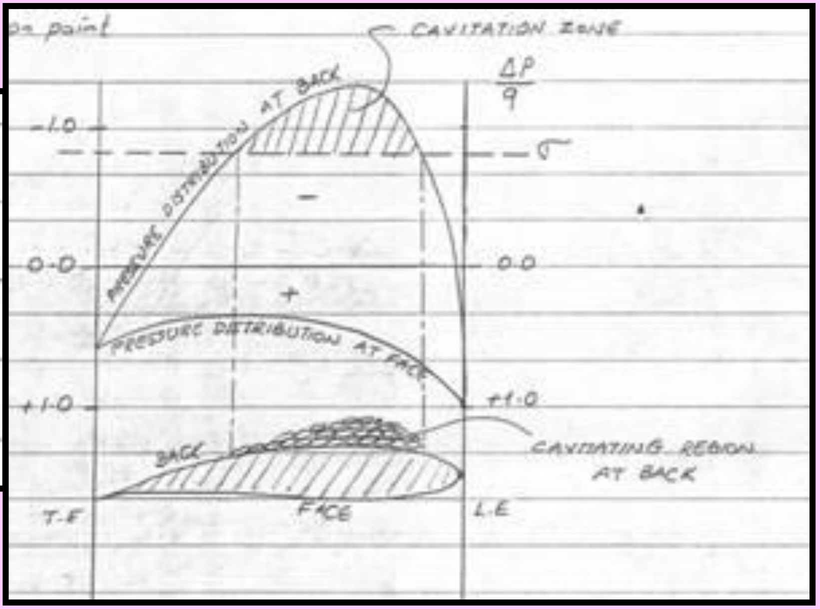
Effect of angle of attack on cavitation

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).

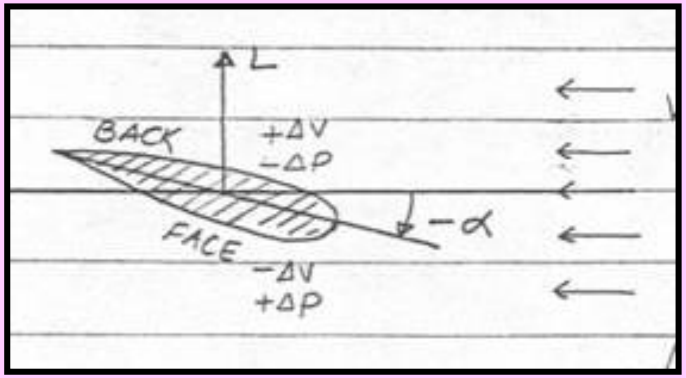
1. Positive angle of attack

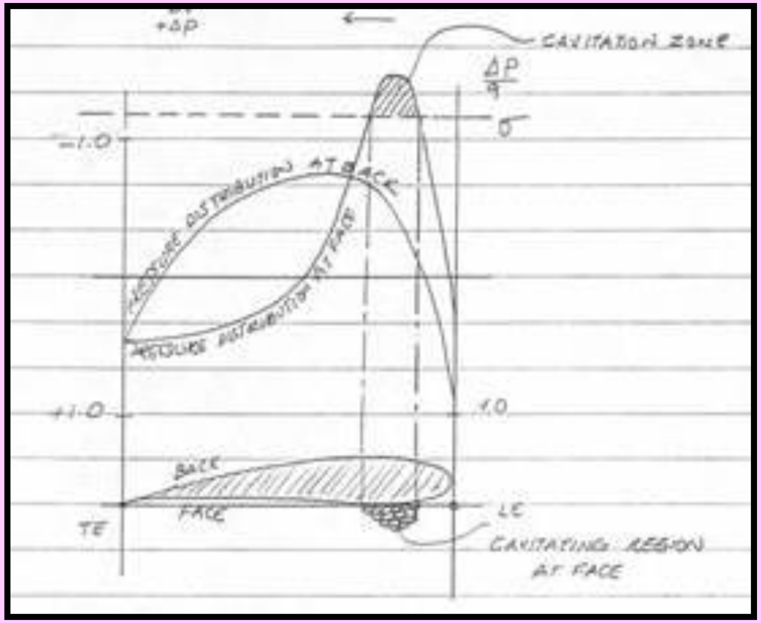




as seen positive angle of attack may cause cavitation at the back of the profile and towards the trailing edge.

2. Negative angle of attack





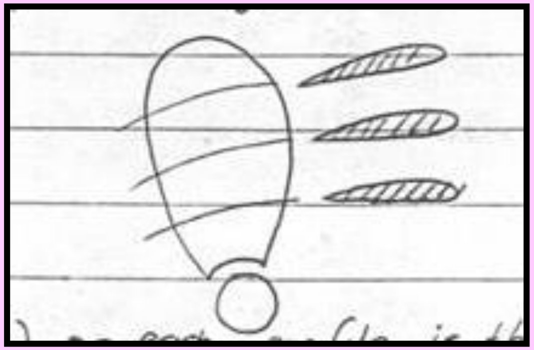
when $\alpha<0$ cavitation zone behind the max thickness region of the profile at the back (i.e. towards trailing edge)

3. Zero angle of attack

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

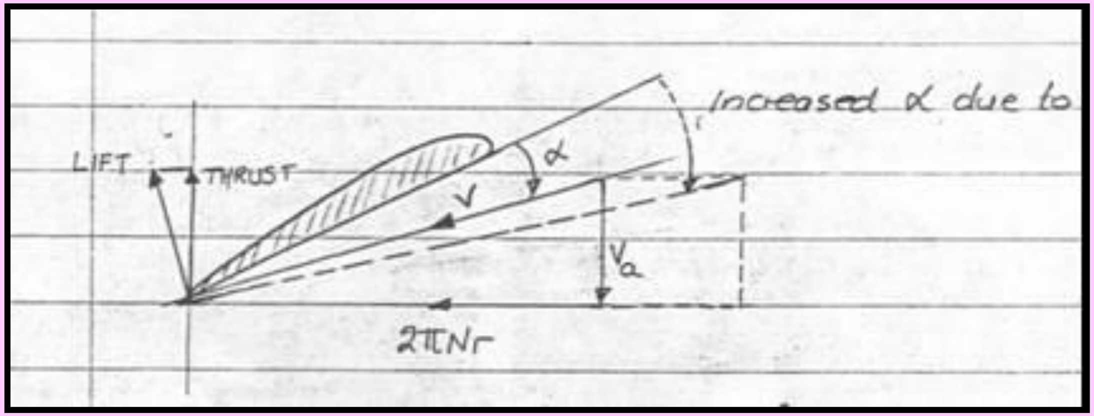
Cavitation on a Propeller Blade

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

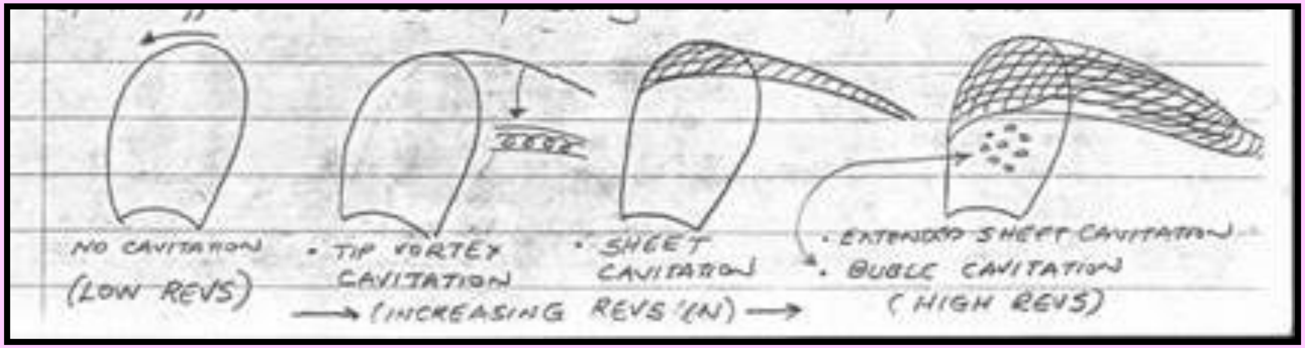


- A lift force (L) on each profile is the integration of the pressure (∆P) along each profile chord.

- Now let us gave a look how changing angle of attack of a propeller blade (α) influences the extend a position of cavitation.



- As can be seen in the previous figure, α can be increased by keeping V_a constant and increasing revs (N).
- This rotational speed effect will result following cavitation paterns.



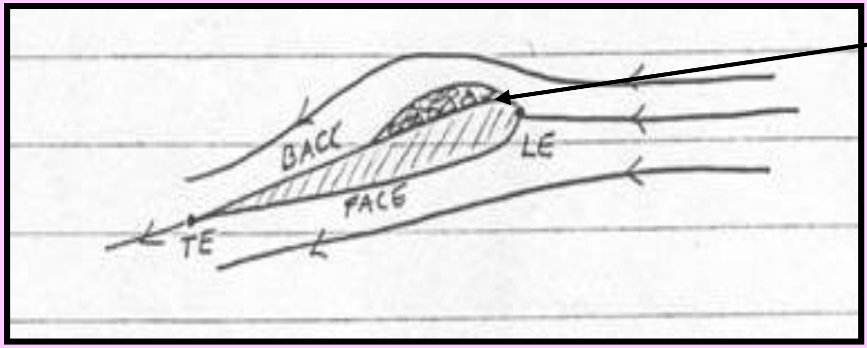
Types of Cavitation

Types of Cavitation

- In the following we investigate the types of cavitation depending upon;
  - Location on the blade of a propeller
  - Physical appearance

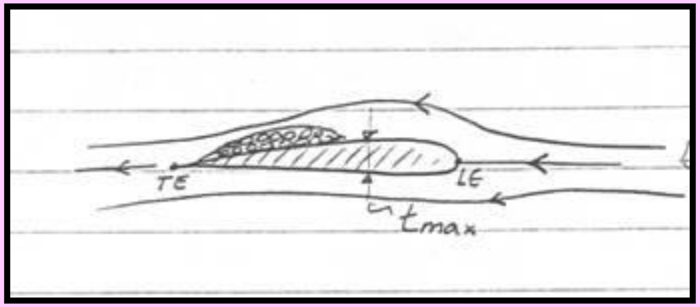
Depending upon LOCATION ON A BLADE - 1

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



Back cavitation near L.E.

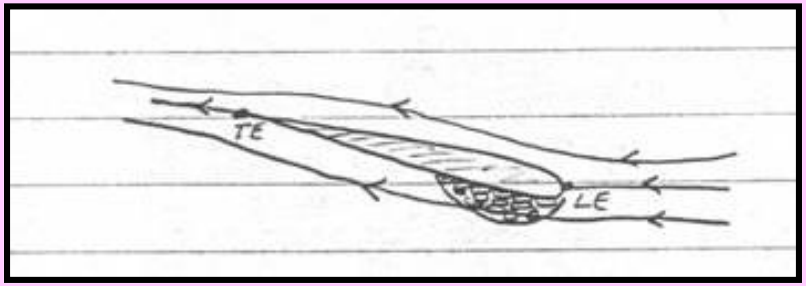
- Back cavitation (towards T.E.) (i.e. $\alpha\sim0$)



Back cavitation beyond the max thickness (t_{max} point)

Depending upon LOCATION ON A BLADE - 2

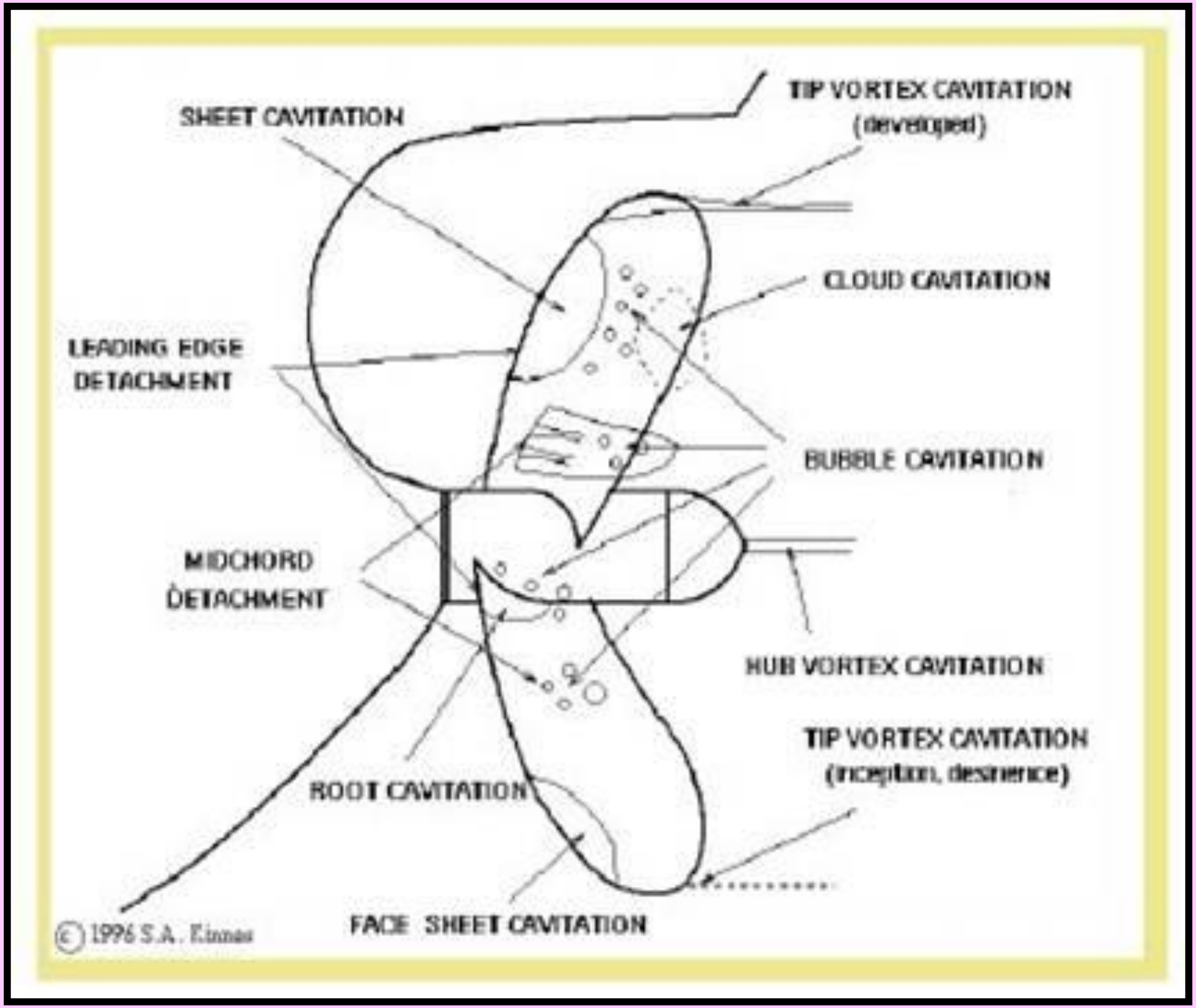
- Face cavitation (i.e. $\alpha<0$)



Face cavitation near L.E.

Depending upon
PHYISICAL APPERANCE OF CAVITATION

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



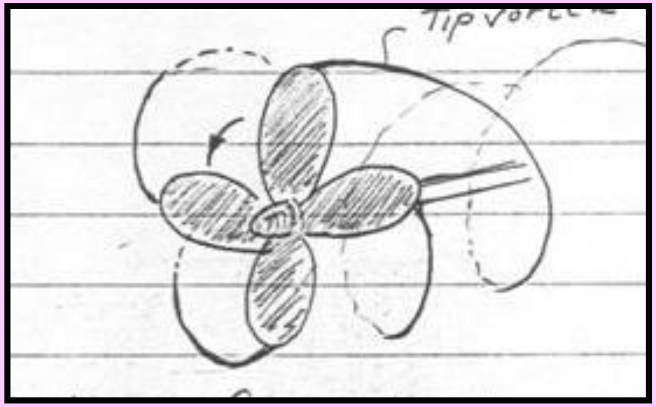
Types of cavitation

- The main parameter controlling the appearance of the cavitation patterns is the “pressure gradient”.
- However, cavitation has many different appearances (e.g. One can count up to 24) and the judgment of the effect is very complex.
- Therefore the previous list is the main types which are discussed as follows

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

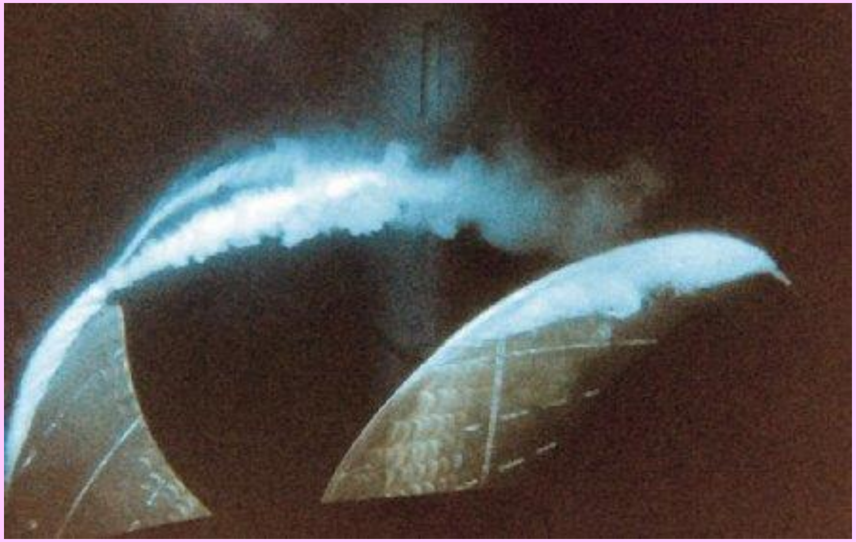
- The tip vortex cavitation is normally first observed some distance behind the tips of the propeller blades which is said to be “unattached” but as the vortex becomes stronger, either through higher blade loading or decreasing in σ, it moves towards the blade tip and ultimately becomes attached.



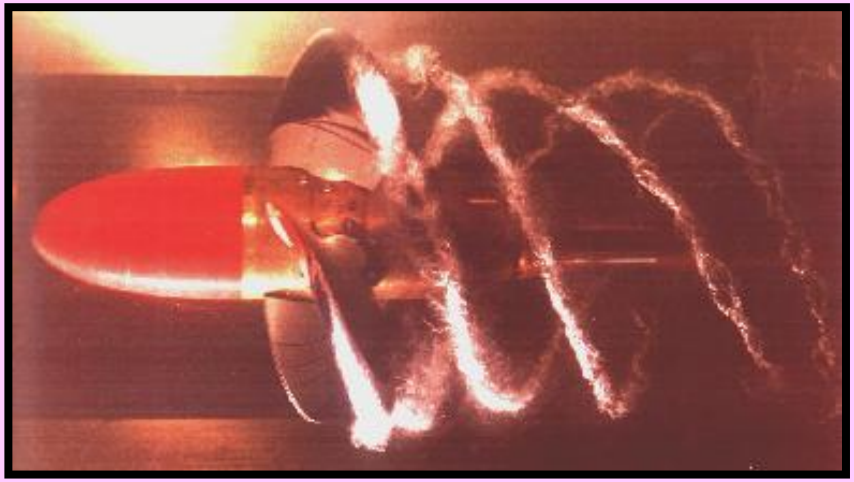
- Tip vortex cavitation depends on the local flow angle on the tip of the propeller blade and can normally be minimized by a reduction of the loading at the tip.

- Cavitation of the vortices which emanate from propeller blade tips is a rather poorly understood phenomenon at this time, and this is partly due to a general lack of understanding of the complex flow regime which exists at the propeller tip.

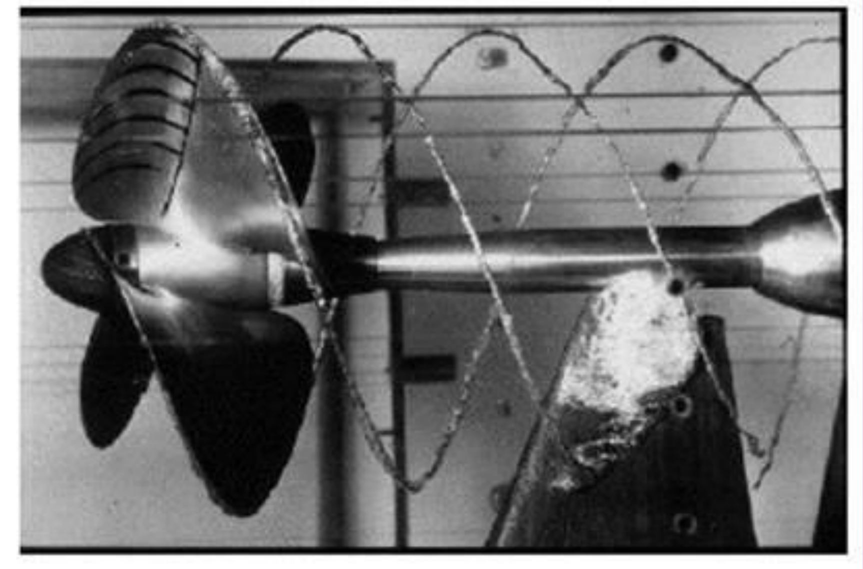
- Tip vortex cavitation is particularly important in the design of ‘***silent*** ' propellers, as a cavitating vortex represents a significant source of noise and therefore dominates the above mentioned cavitation inception speed.



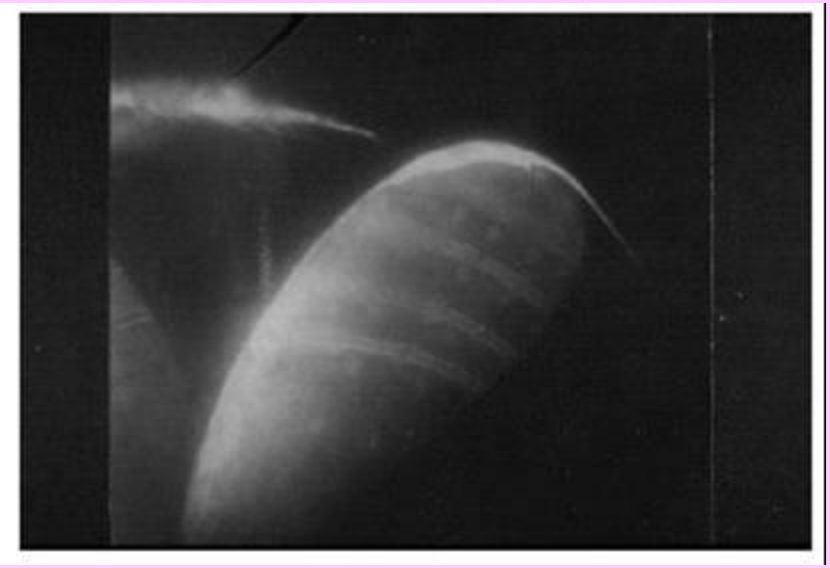
Full scale Cavitation on a container ship propeller



Tip vortex cavitation in model scale



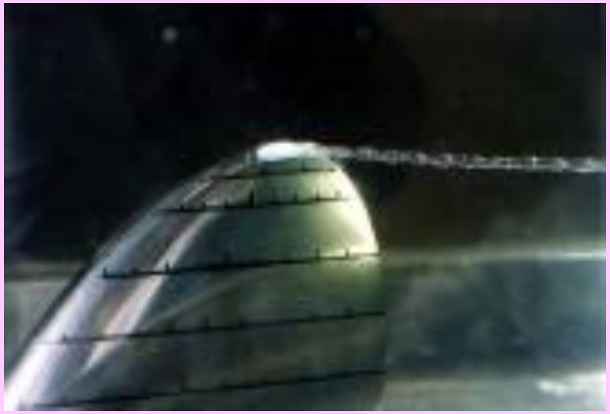
TVC(developed)



TVC (Inception)

(just started)

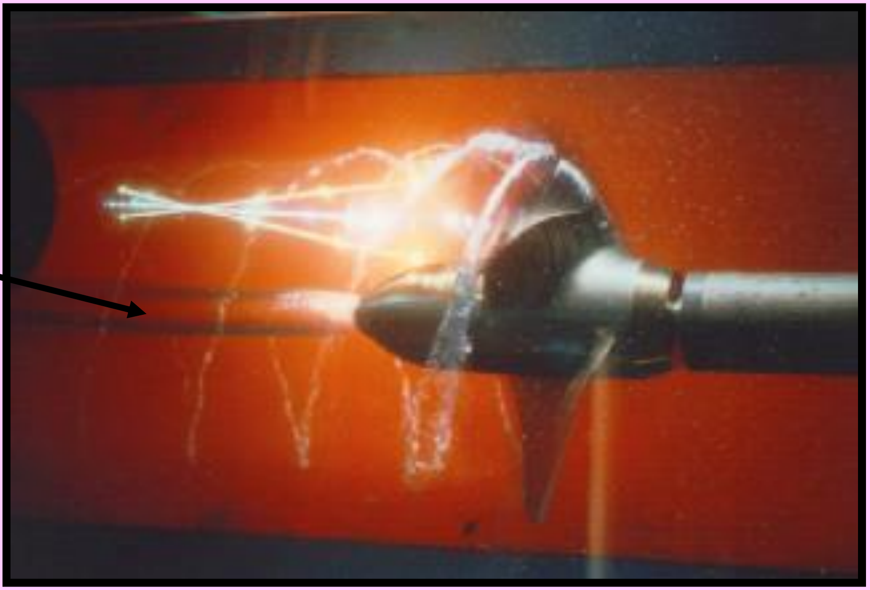
Finite span hydrofoil with no swept-back angle



Finite span hydrofoil with swept-back angle = 30deg.

Hub Vortex Cavitation

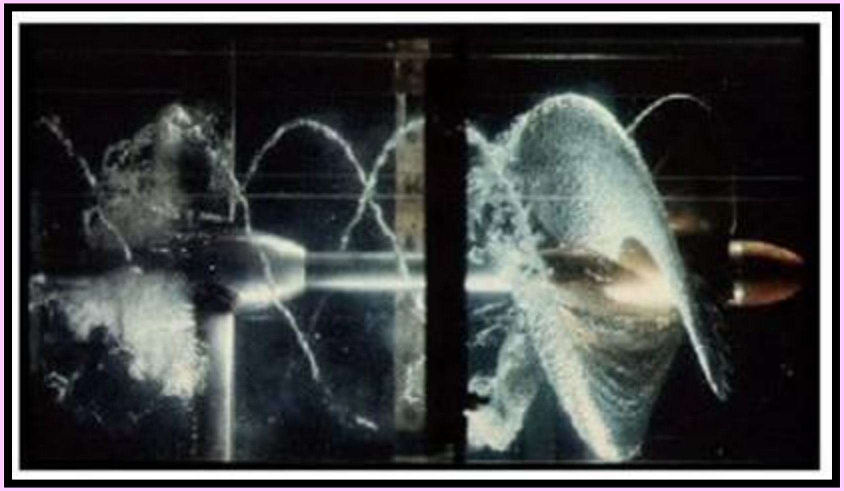
- The hub vortex is formed by the combustion of individual vortices shed from each blade root and although individually these vortices are unlikely to cavitate, under the influence of a converging propeller cone the combination of the blade root vortices has a high susceptibility to cavitate.
- When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



H.V. directly goes to the rudder

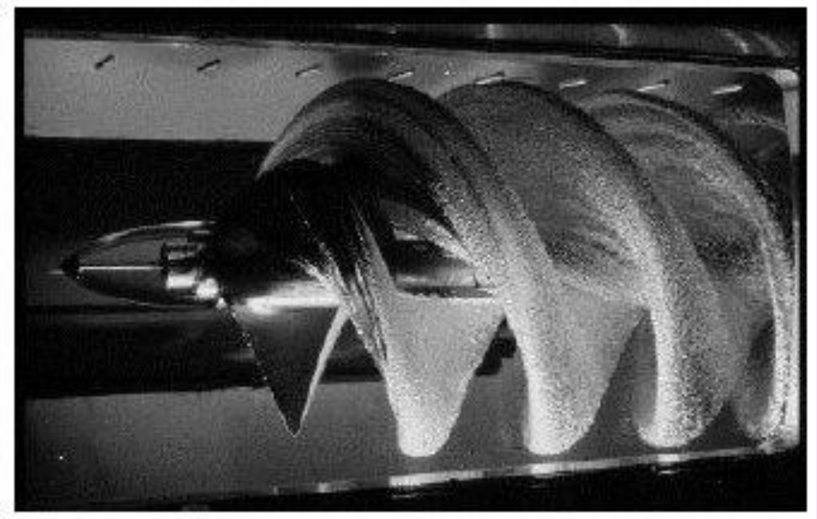
Sheet Cavitation

- 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.



Sheet cavitation – back side

- Conversely if the sections are operating at negative angle of attack, the sheet cavitation may initially appears on the face of the blade.



- The sheet cavitation occurs when a leading edge suction peak is lower than the vapor pressure (i.e. $C_p > \sigma$)

- If the angle of incidence increase in magnitude, or cavitation number decreases, then the extent of the cavitation over the blade will grow both chordwise and radially.
- As a consequence the cavitation forms a sheet over the blade surface whose extent depends upon the design and ambient conditions.
- Sheet cavitation is attached to the foil and the flow moves around the sheet.
- The pressure in the cavity is approximately equal to the vapor pressure.

- 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.

- The rear of the cavity is smooth in such cases.

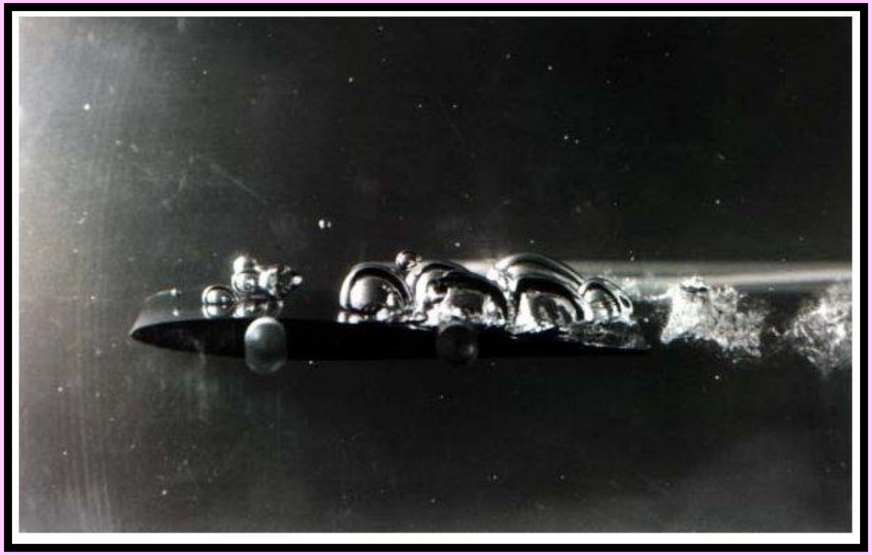
- When the tip of the blade is unloaded, as often case for the naval propellers, the length of the sheet cavity decreases towards the tip.

- The rear of the cavity becomes cloudy as shown in the following figure.

- Steady sheet cavitation is usually harmless while the unsteady sheet cavitation could create problems

Bubble Cavitation

- Bubble cavitation is primarily affected by the pressure distribution which causes high suction pressure in the midchord region of the blade section.



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

http://www.fluidlab.naoe.t.u-tokyo.ac.jp/Research/CavPictures/index.html.en

- Thus the combination of camber line and section thickness play important role on the susceptibility of a propeller toward bubble cavitation.

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

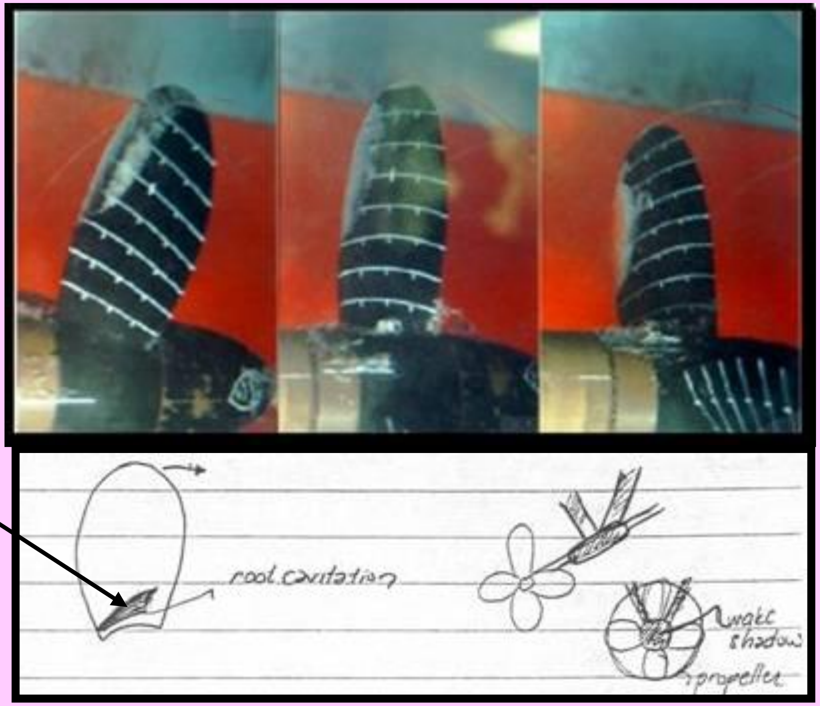
- For example near the root of CP propeller where the chord length is restricted and strength requires thick blade sections.

- This foil exhibits a fairly clean "sheet" cavity. Although near the end of the cavity, you may notice some "bubble" cavitation. Notice that the cavity does not begin at the leading edge of the foil. (The leading edge is the very front of the foil.)

- Since bubble cavitation normally occurs first in the mid-chord region, it tends to occur in non-separated flows.
- In contrast to the sheet cavity there will be no separation between the cavitating flow and blade surface.
- As its name applies, appears in individual bubbles growing, sometimes quite large in size, and collapsing rapidly over the blade surface.
- Therefore when the bubbles collapse it creates serious destructive force which causes erosion and vibration.
- This form of cavitation should be ***avoided***.

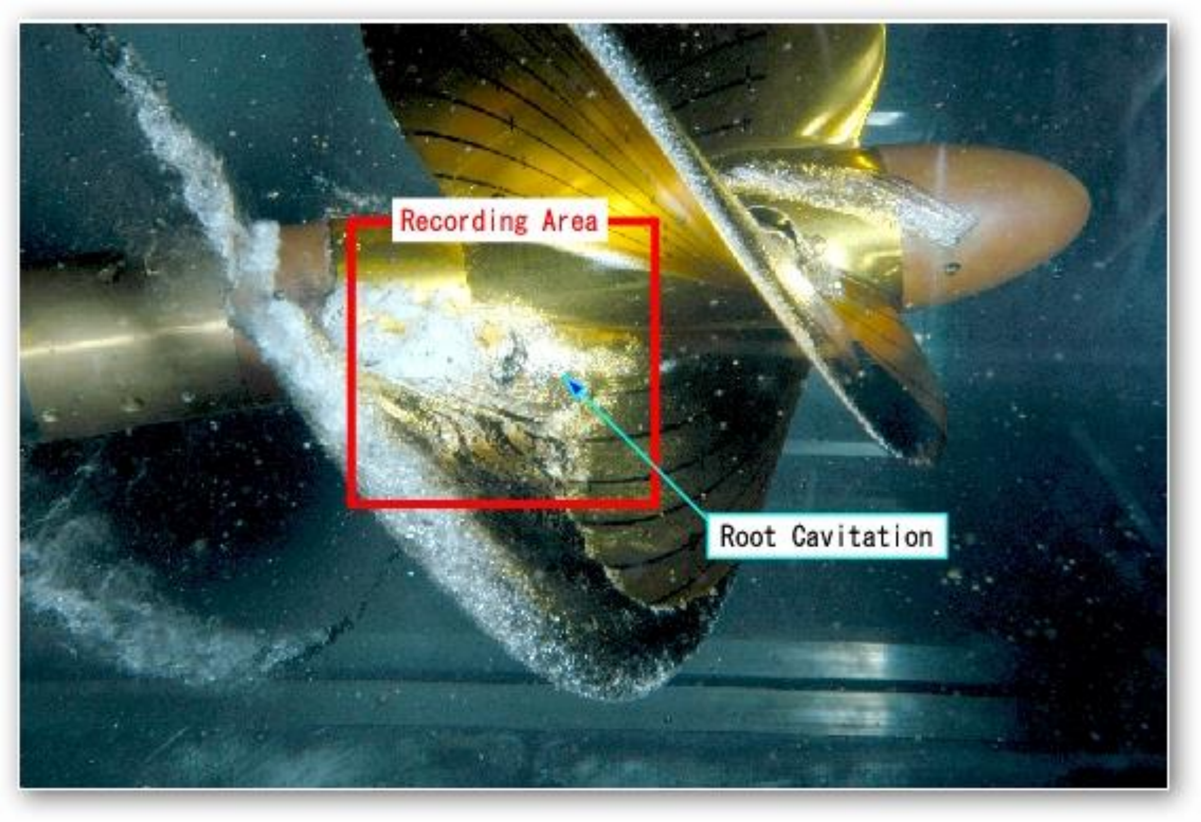
Root Cavitation

- 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.



Root Cavitation

- Root cavitation phenomena on a propeller model was filmed with a high-speed video camera (HPV-1, Shimazu Corporation). The camera can record 1000000 frames per second at maximum frame rate. Condensation and re-expansion of the cavity are observed clearly in the captured images..
- Ref: http://images.google.com.tr/imgres?imgurl=http://www.nmri.go.jp/fluids/topics/highspeedcamera/english/exphighspeedcamera.files/example.jpg&imgrefurl=http://www.nmri.go.jp/fluids/topics/highspeedcamera/english/exphighspeedcamera.html&usg=__a6FUw-XEtYsewtu2dG_SJ2IX6ZE=&h=361&w=545&sz=218&hl=tr&start=6&um=1&tbnid=xyXwXv2fEDPb1M:&tbnh=88&tbnw=133&prev=/images%3Fq%3Dcavitation%26hl%3Dtr%26sa%3DN%26um%3D1



Root Cavitation on Small Commercial Propellers

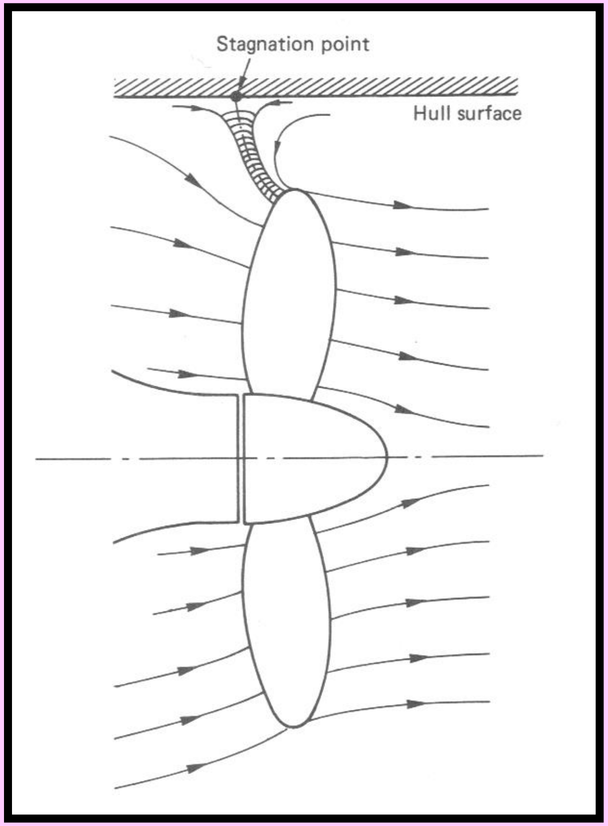
- Root cavitation is generally uncommon.
- It is most often found in high speed, highly loaded propellers.
- It is generally indicated by a pitting on the suction side (back) of the blade root area near the point of maximum thickness.
- One cure for root cavitation is based on relieving some of the suction side lift by drilling a small hole through the root to the pressure (face) side.

- This hole typically is located at the mid-chord of the blade, just outside of the root.
- One 10 mm (3/8 inch) hole is typical for propellers of about 800 to 1000 mm (32 to 38 inch) diameter.
- Careful matching of the location of the holes between blades must be observed, and the edges of the holes should be softened with a chamfer.
- According to one respected source, the key to successfully curing root cavitation is to be sure to drill the holes parallel to the shaft line, not perpendicular to the blade.

- Reference: http://www.hydrocompinc.com/techrpts/RPT112.htm

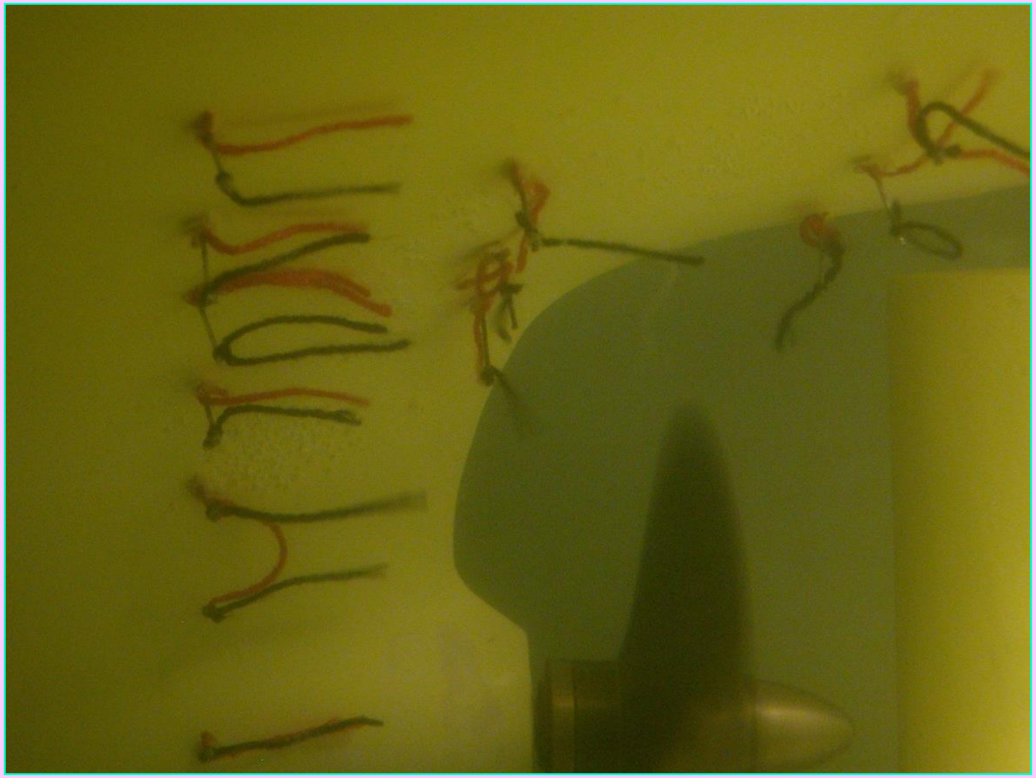
Propeller-Hull Vortex (PHV) Cavitation

- 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.



- It is postulated that at high loading the propeller becomes starved of water due to the precense of the hull in the upper part of the aperture ahead of the propeller.
- To overcome this starvation the propeller endavours to draw water from astern, which leads to the formation of a stagnation streamline from the hull to the propeller disc.

- 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



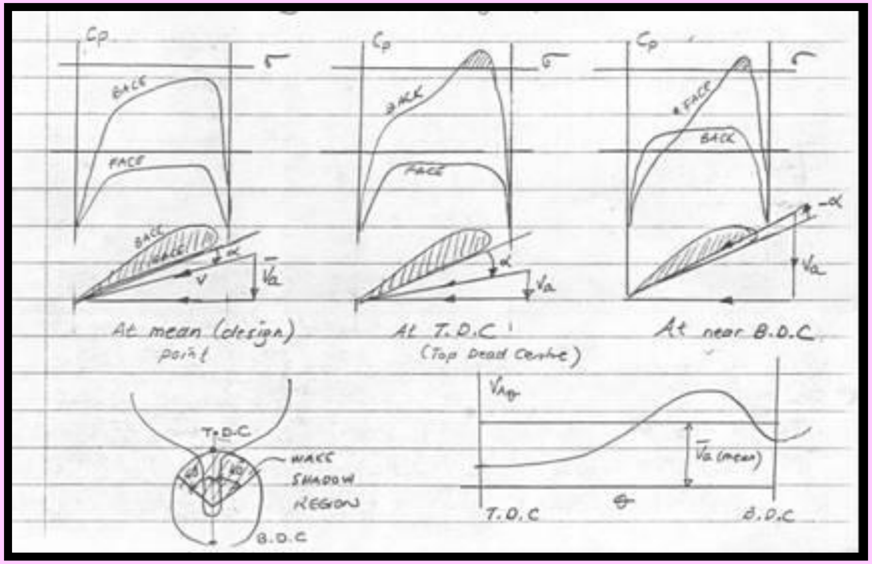
Visualization of the flow when the propeller is in operation. (Propeller hull vortex can be slightly seen within the circular line).

Unsteady Sheet (Cloud) Cavitation

- Cloud cavitation is frequently to be found behind strongly developed steady sheet cavities and generally in moderately separeted 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.

Unsteady Sheet (Cloud) Cavitation

When propeller blade operates in non-uniform wake the angles of attack of the blades will vary during one revolution and hence the cavitation develops as in the following depending on V_a (advance velocity) and hence angle of attack

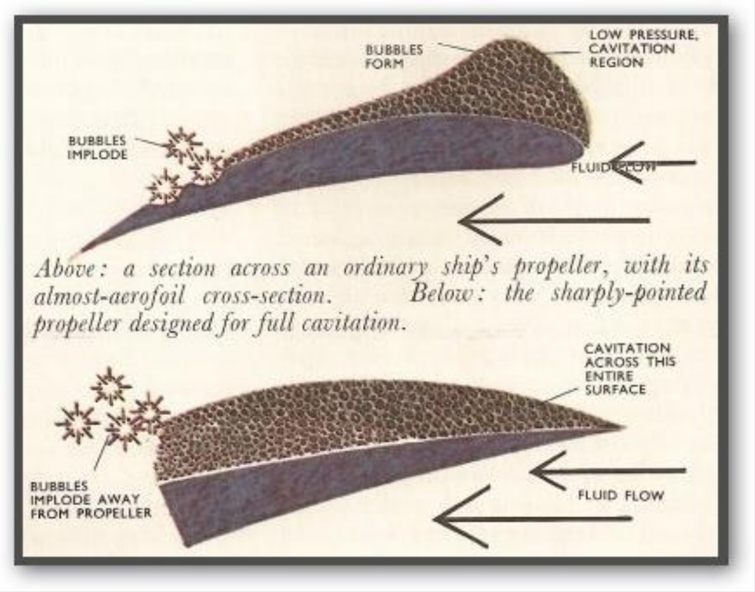


Supercavitation

The pictures above show "partial cavitation" which length is shorter than the chord length of the foil.

On the other hand we sometimes see

"supercavitation" which is longer than the foil and surrounds the foil. Supercavitation is almost stable and steady.



Above: *a section across an ordinary ship's propeller, with its almost-aerofoil cross-section.* *Below:* *the sharply-pointed propeller designed for full cavitation.*

Effects of Cavitation on Propellers

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.
- When cavitation occurs depending upon its extend and severity, the propeller may suffer from
  - Performance breakdown
  - Noise , Vibration , Erosion

Effects of Cavitation on Propellers - Performance Breakdown 1

- Partial cavitation on a propeller blades 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 (RPM) is low.

Effects of Cavitation on Propellers - Performance Breakdown 2

- 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 effects is included in K_T, K_Q and η figures as correction.

Effects of Cavitation on Propellers - Noise 1

- There are four principal mechanism by which a propeller can generate pressure waves in water and hence give rise to a noise signature. These are
  - 1 – the displacement of water by blade profile
  - 2 – the pressure difference between the suction and pressure surfaces of the blades in rotation
  - 3 – the periodic fluctuation of the cavity volumes by operation of the blades in the variable wake field behind the vessel
  - 4 – the sudden collapse of vapour filed bubble or vortex

Effects of Cavitation on Propellers - Noise 2

- Clearly the first two causes (due to the boundary layer effects) are associated with propeller in either its cavitating or non-cavitating state while the latter two are cavitation dependant phenomena.

- Therefore propeller noise has two principal constituents:

  1 – non-cavitating

  2 – cavitating component

Effects of Cavitation on Propellers - Noise 3

- The non-cavitating noise although not practical for most merchant ships, is of considerable interest for naval vessels such as antisubmarine frigates, who rely on being able to operate quietly in order to detect potential threats by its sonar.
- A designer endeavors to extend the non-cavitating range of operation of the vessel as far as possible.

Effects of Cavitation on Propellers - Noise 4

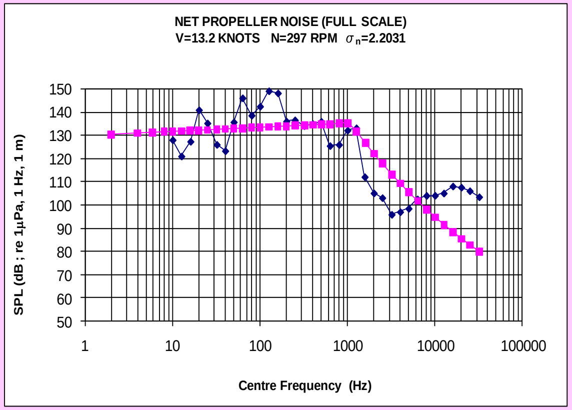
- Propeller noise comprises a series of periodic components or tones, at blade rate and its multiples

$$B.R. = k\frac{N \times Z}{60}(\mathrm{Hz}) \quad k = 1, 2, 3, \ldots \quad N = \mathrm{RPM} \quad Z = \mathrm{Blade\ Number}$$

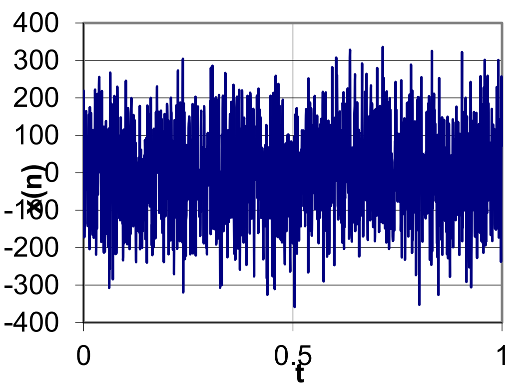
- Typically in the case of 4-bladed propeller operating at say 250 RPM, this gives a blade rate frequency of 16.7 Hz which is just below the human audible range of about 20 – 20.000 Hz.

Noise Simulations - Noise 5

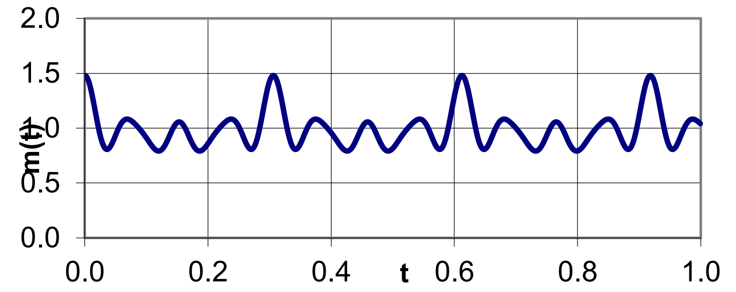
- Propeller noise may be simulated synthetically



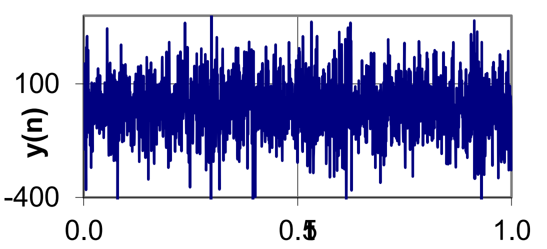
Frequency domain to time domain



Use modulator function



Synthetic propeller noise



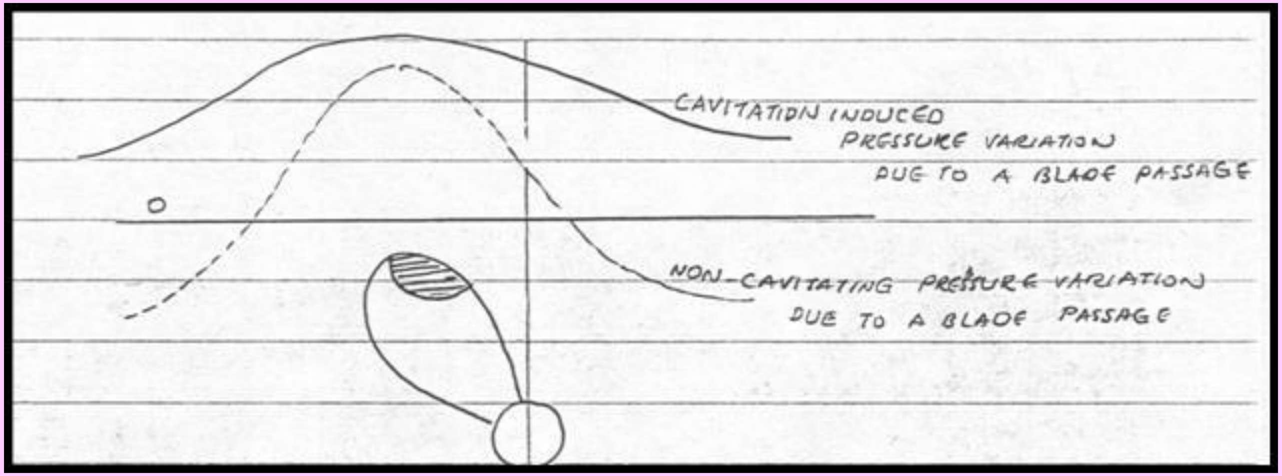
Effects of Cavitation on Propellers - Vibration 1

- Sheet cavitation on a blade can have considerable volume.
- The dynamic behavior of this large volume of vapor generate strong “pressure fluctuations” at frequencies of the BR and its multiples.
- 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.

Effects of Cavitation on Propellers - Vibration 2

- 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.

Effects of Cavitation on Propellers - Vibration 3



The figure shows the pressure disturbance at certain time and blade position.

The pressure due to cavitating blade reaches its max and min everwhere 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.

Effects of Cavitation on Propellers - Vibration 4

- Also the pressure variation due to cavitation induced pressure decreases with 1/r (r is the distance from hull to cavity) while the pressure amplitude of the non-cavitating blade decreases with $1/r^2$, so much faster.

- When the cavitation induced pressures integrated over the hull they present much larger hull vibration forces compared to the non-cavitating pressure induced forces which are much more in cyclic nature (ie + and – around a mean) and the area at which the pressures act is smaller.

Effects of Cavitation on Propellers - Vibration 5

- The area over which the pressure fluctuations are integrated is more important.
- The ships with open flat panels above the propeller suffer from the vibration problems.
- For example open stern container ships, ro-ro ships where the response of the flat plates to these hull pressure is very strong, resulting in vibration.
- Unacceptable hull vibrations can be reduced by
  - Re-designing the aft end and propeller
  - Changing the response (ie natural frequency) of the aft end construction

Effects of Cavitation on Propellers - Vibration 6

- The later 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 ie “tip unloading”

Effects of Cavitation on Propellers - Erosion 1

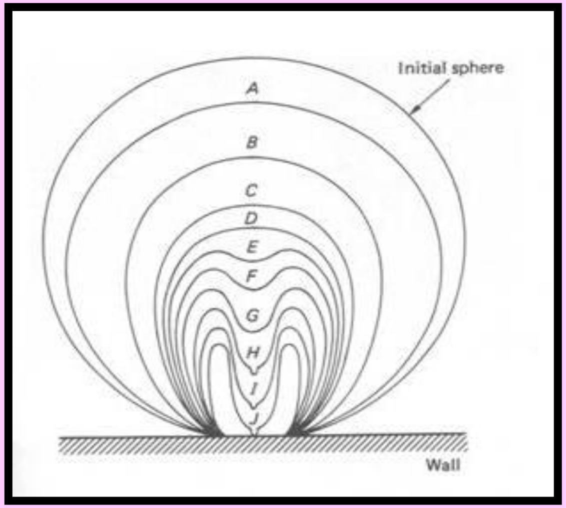
- Generation of a vapor bubble in fluid is a very rapid process.
- When the bubble moves into a lower pressure zone in the fluid, it will expand rapidly while the pressure inside remains very close to the vapor pressure.
- When this vapor filled cavity encounters a high pressure zone in the fluid (e.g.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

Effects of Cavitation on Propellers - Erosion 2

- 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.

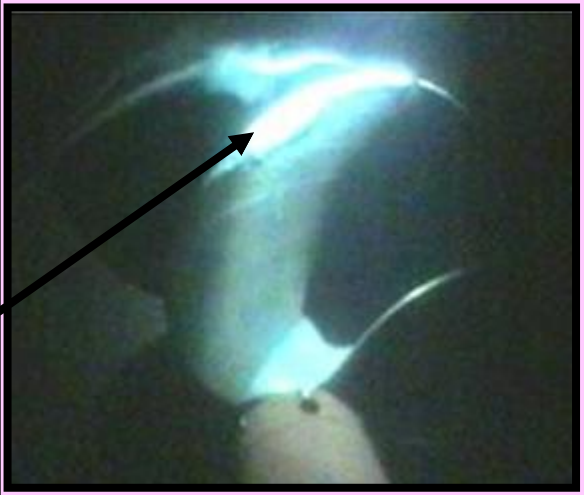
Effects of Cavitation on Propellers - Erosion 3

- The figure shows the result of a computation of an initially spherical bubble collapsing close to a solid boundary, together with a formation of the "Micro jet" directed toward the wall.
- The velocity in this micro-jet is very high and the pressure also can be several of thousands of bars.
- This has a similar effect to the hitting to a wall with very fine hammer head.
- The result will be a pitted surface.



Effects of Cavitation on Propellers - Erosion 4

- During the collapse of the cavity the velocity of the cavity will simply disappear after collapse.
- This, however, never happens.
- For inception of a bubble cavity a small gas bubble (nucleus) is already required.
- During the expansion of this, nucleus gas is collected in the cavity by diffusion.
- At the end of the collapse a small amount of gas at very high pressure remains (the pressure is so high the bubble cavity can radiate light)
- This gas expands again and the bubble cavity "rebounds" as numerous small bubbles.
- These bubbles act again as cavities and collapse again.



Effects of Cavitation on Propellers - Erosion 5

- In this way the collapse of a single bubble cavity can produce a multitude of pits on the surface and very complex noise spectrum as well.
- When a cloud of bubbles collapse simultaneously, the collapse can be more violent than the collapse of single bubbles in cloud.
- This is because the pressure distribution in the cloud during collapse produces a “higher mean pressure” in that region.
- This explains why the collective collapse of bubbles as occurs in cloud cavitation is so erosive.

Effects of Cavitation on Propellers - Erosion 6

İBB Carbon Fiber Ferries - 01

Effects of Cavitation on Propellers - Erosion 6
İBB Carbon Fiber Ferries - 02

Effects of Cavitation on Propellers - Erosion 6
İBB Carbon Fiber Ferries - 03

Design to Minimise Risk of Cavitation

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 was subsequently developed by relating the “Mean Thrust” to the required “Blade Surface Area”.
- Criteria was subsequently developed by relating the mean thrust to the required Blade surface area in the form of a limiting thrust loading coefficient.

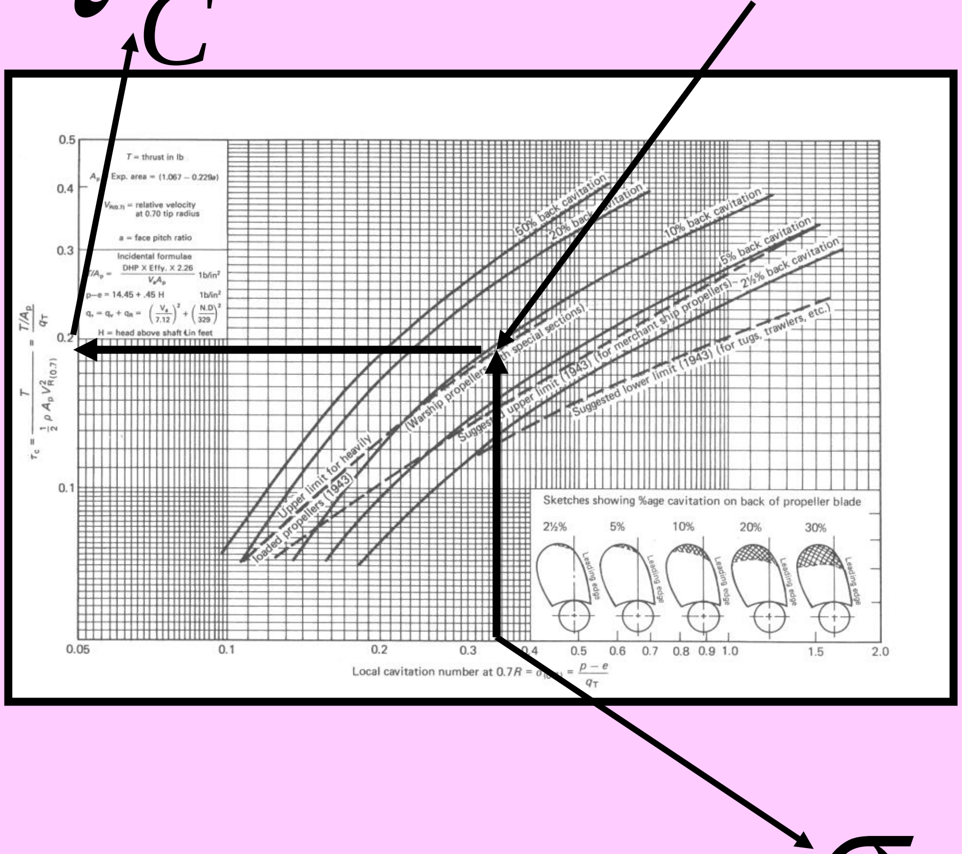
- The first such criterion of T/A_p=77.57 kPa (11.25 lbf/in^2) was derived in the latter part of the 19th century.
- Much of development work was undertaken in the first half of the century in deriving refined forms of these thrust loading criteria for design purposes:
  - Two of the best known are those derived by BURRILL and KELLER

BURRILL’s Criteria

- Burrill ’s method, which was proposed for fixed pitch, conventional propellers, centres around the use of the diagram.
- The mean cavitation number is calculated based on the static head relative to the shaft centre line , and dynamic head is referred to the 0.7R blade section.
- Using this cavitation number $\sigma_{0.7R}$, the thrust loading coefficient τ_c is read off from figure.

Permissible level of back cavitation

τ_C



$\sigma_{0.7R}$

$\tau_c = \dfrac{\frac{T}{A_P}}{q_T}$; Thrust Loading Coefficient

T = Thrust

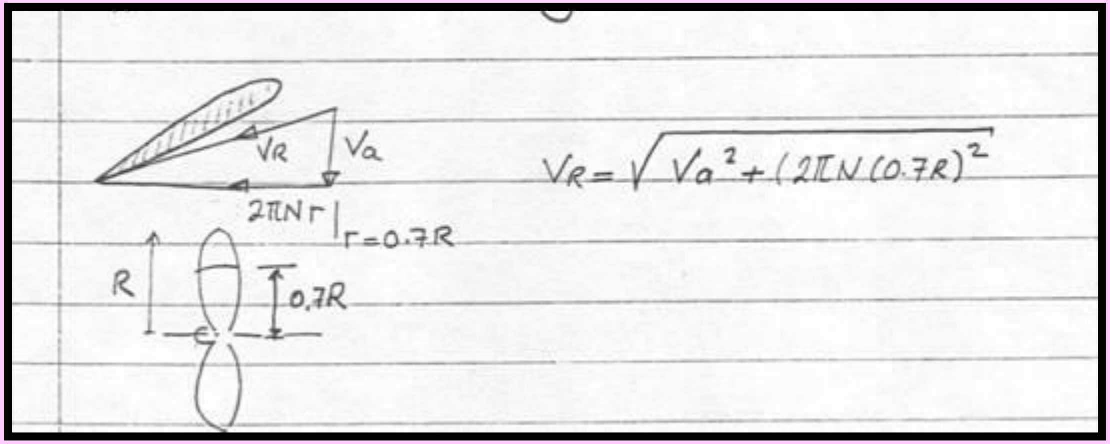
A_P = Propeller Projected Area

P_0 = Statical pressure at shaft center line

e = saturated vapor pressure ($i.e. P_V$)

q_T = dynamical pressure calculated at $r = 0.7R$

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



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

Using Burrill’s Diagram – Parameters and Units 1

$$\tau_c = \frac{{}^{T}\!/\!_{A_P}}{q_T} \quad ; \quad \sigma_R = \frac{P_0 - e}{q_T}$$

$$q_T = \frac{1}{2}\rho V_R^2 = \left(\frac{V_a}{7.12}\right)^2 + \left(\frac{ND}{3.29}\right)^2 \left(\frac{lbs}{in^2}\right) \qquad \begin{cases} V_a \text{ in knots} \\ N \text{ in RPM} \\ D \text{ in feet} \end{cases}$$

or

$$q_T = \frac{1}{2}\rho V_R^2 = \left(11.66 V_a\right)^2 + \left(0.828 ND\right)^2 \left(\frac{N}{m^2}\right) \qquad \begin{cases} V_a \text{ in knots} \\ N \text{ in RPM} \\ D \text{ in meters} \end{cases}$$

Using Burrill’s Diagram – Parameters and Units 2

$$p-e=\text{total static head at shaft } \mathrm{C_L} \text{ - Vapor Pressure}$$

$$=(P_a+\rho gH)-e$$

$$=(14.45+0.45H \quad \left(\frac{lbs}{in^2}\right) \quad \{H \text{ in feet}$$

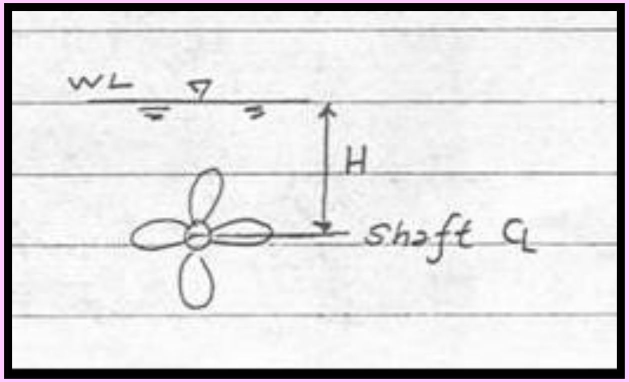
or

$$p-e=99629+10179H \quad \left(\frac{N}{m^2}\right) \quad \{H \text{ in meters}$$

$$\frac{T}{A_P}=\frac{2.26P_D\eta_0}{V_aA_P}\left(\frac{lbs}{in^2}\right) \quad \begin{cases} P_D \text{ in HP} \\ V_a \text{ in knots} \\ A_P \text{ in feet}^2 \end{cases}$$

or

$$\frac{T}{A_P}=\frac{1941.3P_D\eta_0}{V_aA_P}\left(\frac{N}{m^2}\right) \quad \begin{cases} P_D \text{ in kW} \\ V_a \text{ in knots} \\ A_P \text{ in meters}^2 \end{cases}$$



- In using Burrill's diagram from the value of τ_c read off from the diagram the projected area for the propeller can be calculated from the following;

$$\boxed{A_P = \frac{T}{\tau_c q_T}}$$

- To derive the expanded area from the projected area, Burrill provides the emprical realtionship which is valid for conventional propeller forms only;

$$\boxed{A_E \cong \frac{A_P}{\left(1.067 - 0.229\,{}^{P}\!/\!{}_{D}\right)} \qquad (A_E \approx A_D\ assumed)}$$

- Expanded blade area ratio - EAR

$$\boxed{\frac{A_E}{A_0} \cong \frac{A_E}{\frac{\pi D^2}{4}}}$$

KELLER ’s Criteria

- The alternative blade area estimation is the Keller Formula

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

$$\begin{array}{l} K = 0.2\,\text{for single screws} \\ \left.\begin{array}{l} K = 0.0\,\text{for fast naval ships} \\ K = 0.1\,\text{for slow merhant ships} \end{array}\right\}\text{Twin Screws} \end{array}$$

- Where
  - P_0 is the static pressure at the shaft C_L in Pa
  - P_V is the vapor pressure in Pa (~1700 N/m^2)
  - T is the propeller thrust (N)
  - Z is the blade number
  - D is the propeller diameter in meters

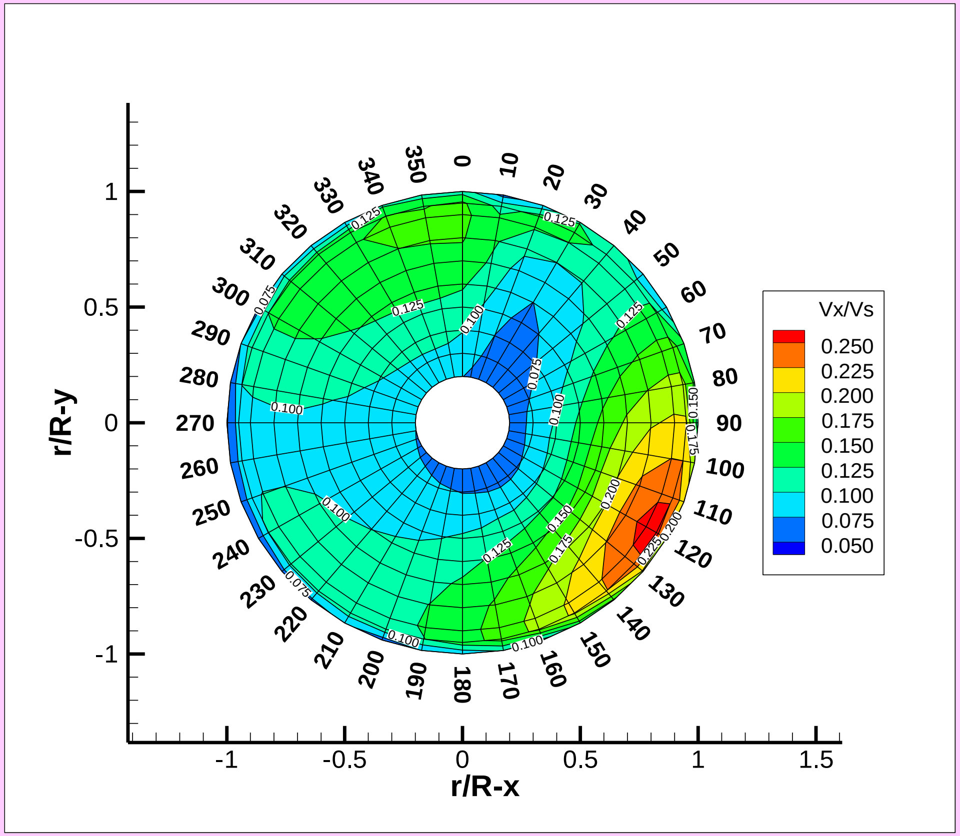
- Both the Burrill and Keller criteria have been used with considerable success by propeller designers for estimating the blade area.

- In many cases, particularly for small ships and boats, these methods and even more approximate ones perhaps from the major part of the cavitation analysis;

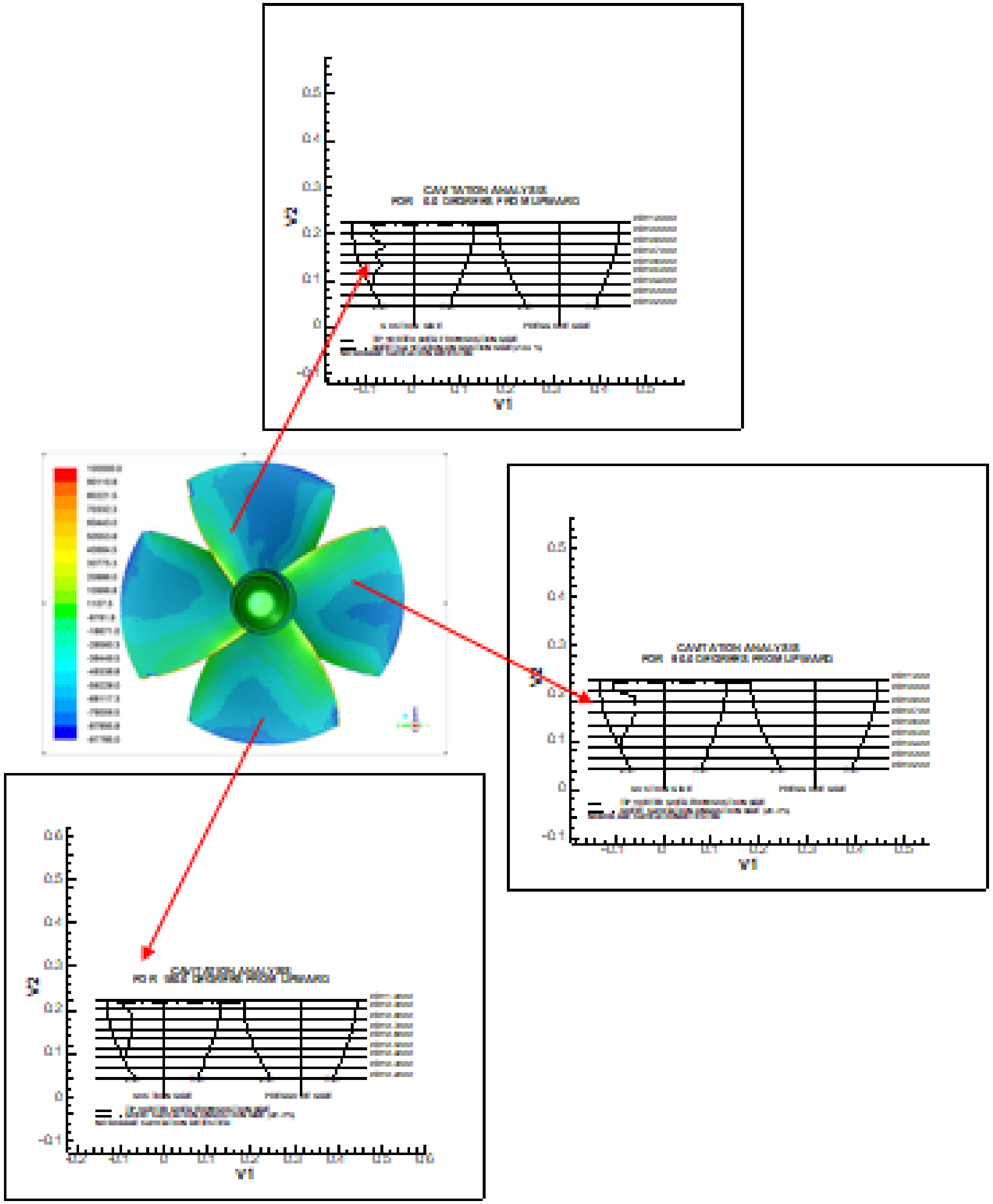
- However for larger vessels and those for which measured model wake field data is available, the cavitation analysis should proceed considerably further to the evaluation of the pressure distribution around the blade sections and their tendency towards cavitation inception and extent.

Computational Predictions -01

- Wake Field is known either by computation or experiment



Amphibious armored vehicle



Computational Predictions - 02

- Wake Field is known either by computation or experiment

Warship Example - 02

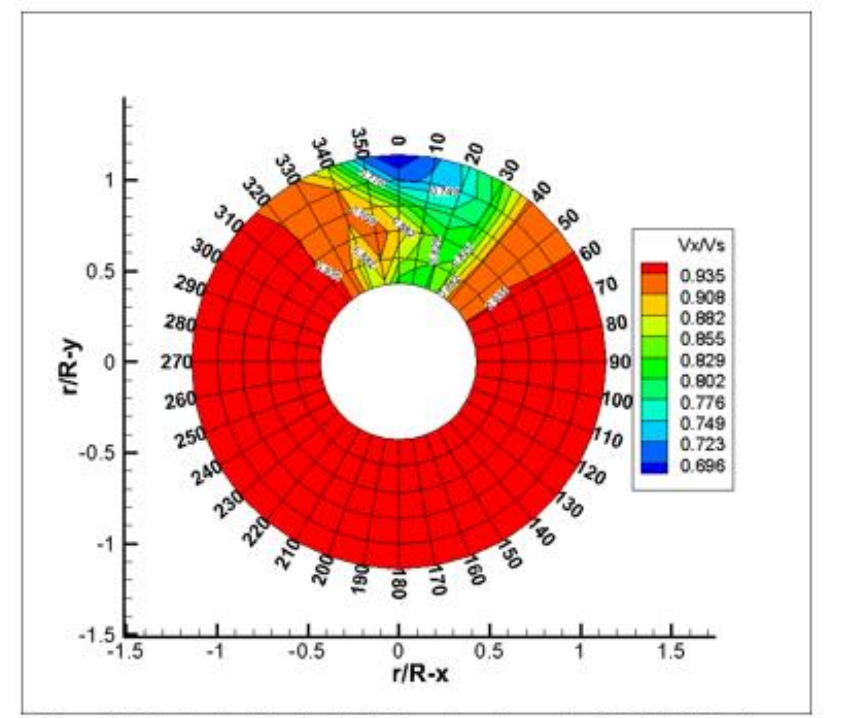


Figure 3.2. Nominal axial wake distribution: Experimental by LDV. SVA Potsdam.

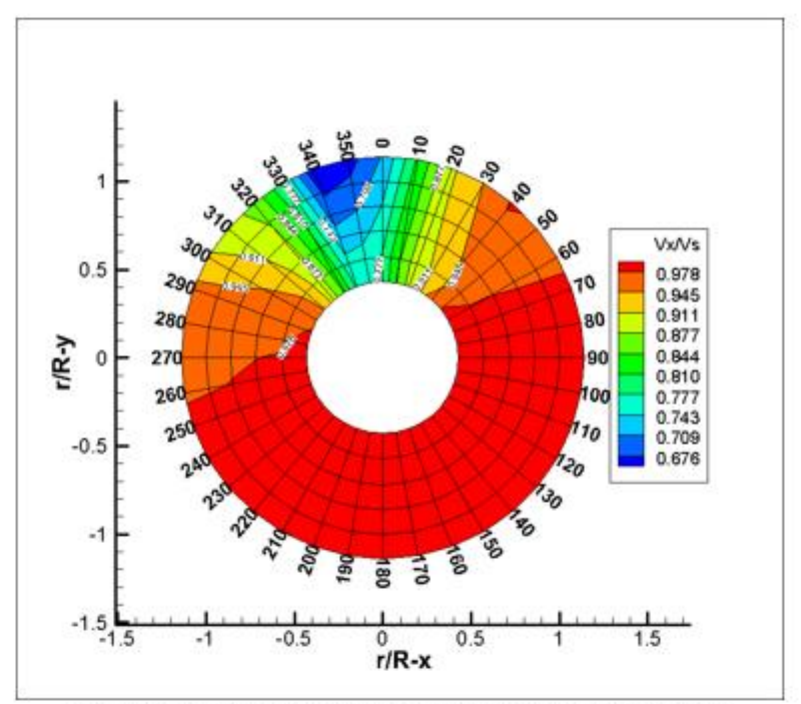
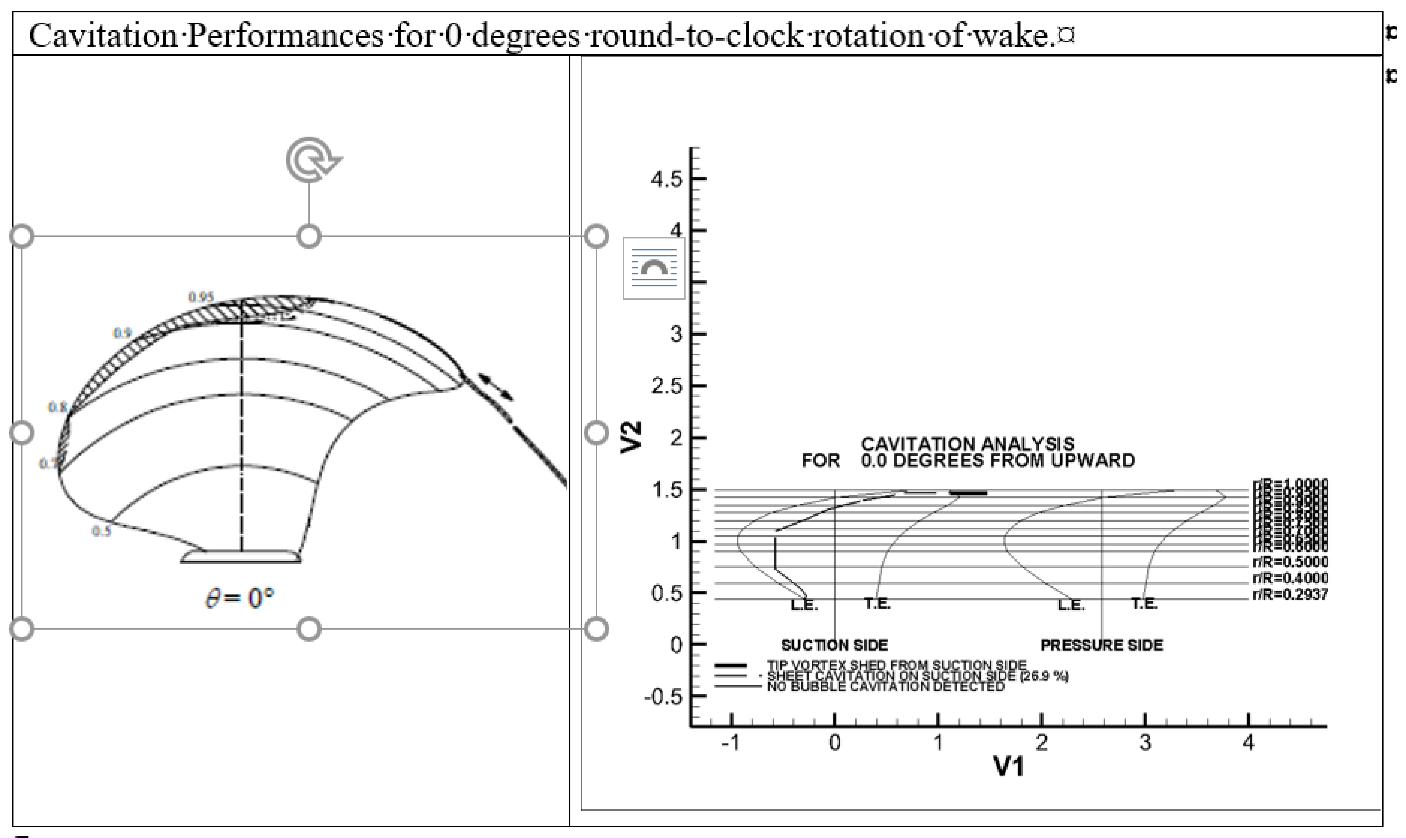


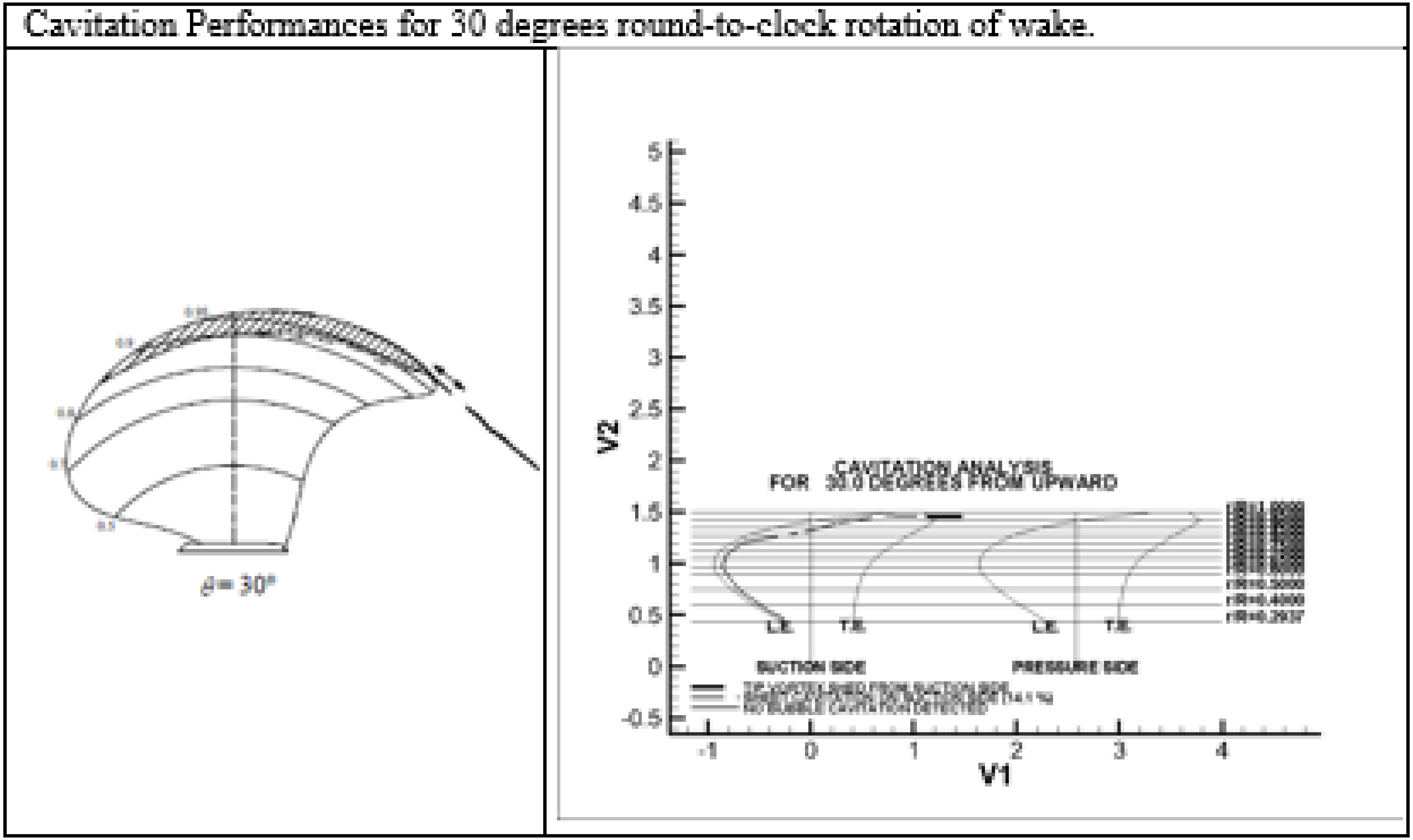
Figure 3.3. Nominal axial wake distribution: Computational by CFD. Miltek.

Warship Example - 02



Cavitation·Performances·for·0·degrees·round-to-clock·rotation·of·wake.¤

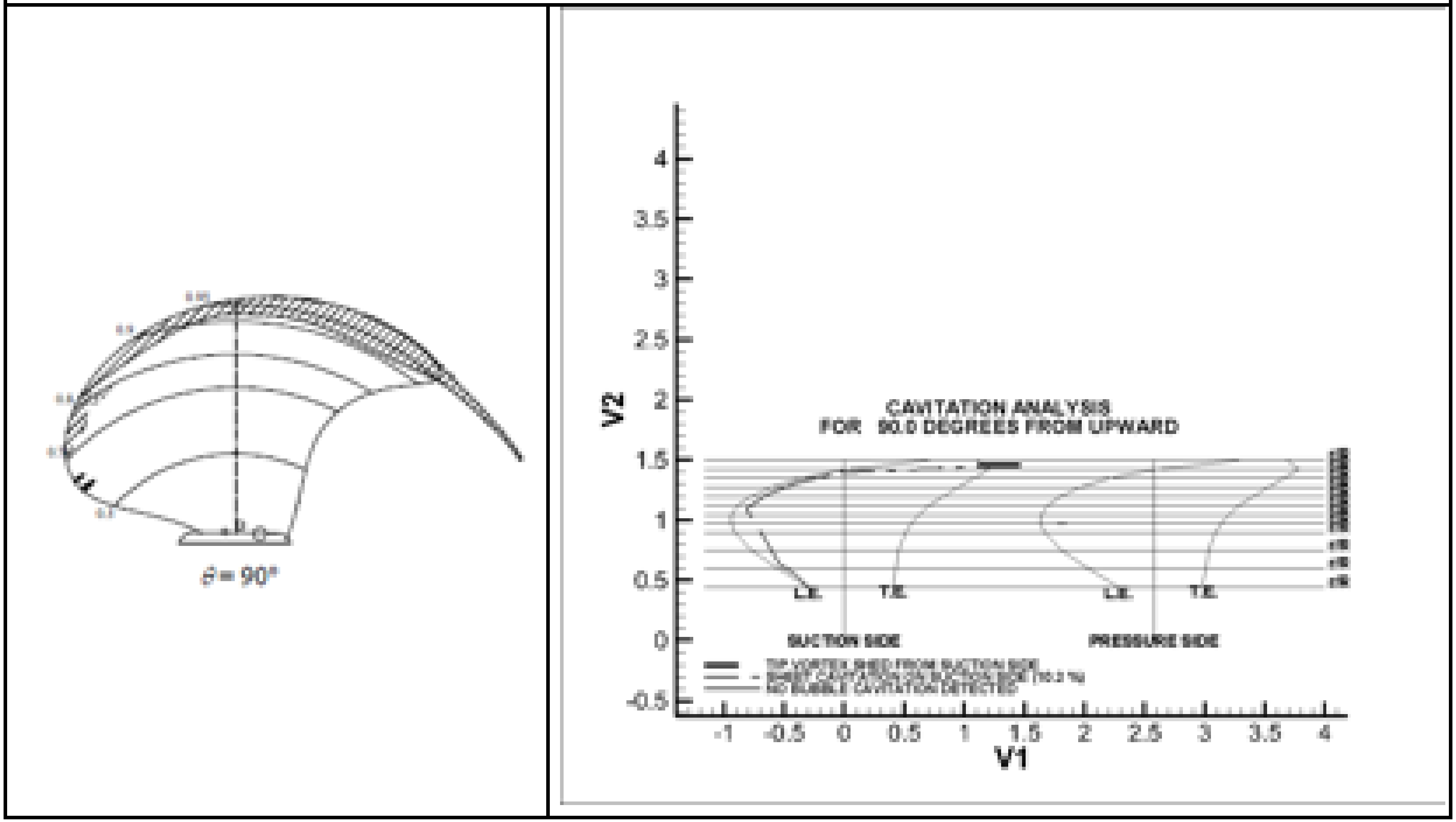
Warship Example - 03



Cavitation Performances for 30 degrees round-to-clock rotation of wake.

Warship Example - 04

Cavitation Performances for 90 degrees round-to-clock rotation of wake.



Inception of Ventilation

- Propeller ventilation is when surface air is drawn into the propeller disk.
- This can occur when a propeller does not remain submerged dynamically during motions or stticaly at light draft.

Inception of Ventilation - Prediction

- The inception of ventilation correlates to thrust loading.
- Greater thrust means more suction side vacuum, which in turn, means a greater likelihood of ventilation.
- The implementation of the method herein converts the relationship so that a limiting critical speed of advance, $V_{A\text{-}CRIT}$, is used as the indicator of ventilation.
- Non-ventilating performance is maintained when $V_A > V_{A\text{-}CRIT}$.

Inception of Ventilation - Prediction

- **VARIABLES**
- D = diameter [m]
- G = gravitational constant [9.81 m/s2]
- Hs = hub immersion below WL [m]
- n = shaft speed [revs/s]
- P = pitch [m]
- R = radius [m]
- V = ship speed [m/s]
- w = wake fraction

$$V_{A-CRIT} = Pn\left[1 - \frac{0.416\, {}^{H_S}\!/_{R} - 0.004}{0.854 + 0.34e^{(-6.1K)}}\right]$$

$$K = \frac{9.81}{n^2 D} \quad (K : Tip\ speed\ parameter)$$

$$V_A = V(1-w) \quad (Speed\ of\ advance - m/s)$$

- **RANGE OF APPLICTION**
- Hs/R = 1.0 – 1.5
- K = 0.05 – 0.44

- Ref: Predicting the inception of ventilation, Hydrocomp technical report no:134, 2003

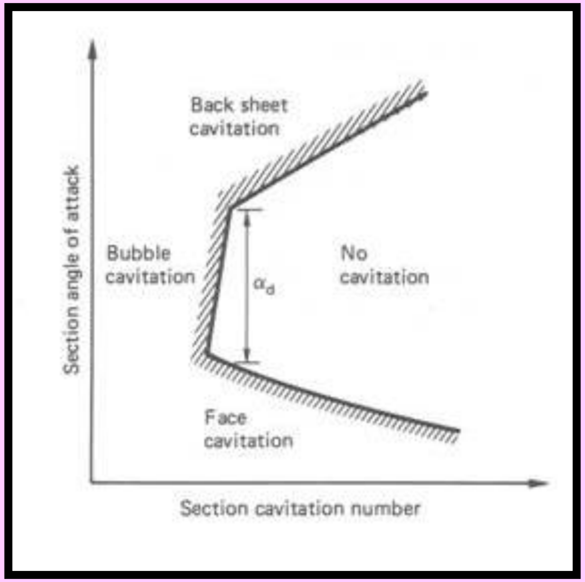
Inception of Ventilation – Prediction Example

- $D = 2.50$ ft , $G = 32.2$ ft/s^2 , $H = 1.25$ ft
- $n = 13.0$ revs/s (shaft speed)
- $P = 2.50$ ft , $R = 1.25$ ft , $V = 20.3$ ft/s (12 kts)
- $w = 0.06$

- $H/R = 1.0$, $K = 0.076$
- $V_A = 19.1$ ft/s , $V_{A\text{-CRIT}} = 20.0$ ft/s
- **Conclusion**: V_A is less than $V_{A\text{-CRIT}}$, so ventilation is predicted to occur.

Cavitation Bucket Diagrams

- For propeller blade section design purposes the use of “cavitation bucket diagrams” is valuable, since they represent in a two-dimesional sense the cavitation behaviour of a blade section.
- 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;
  - Cavitation free area inside the bucket
  - Back sheet outside the bucket
  - Bubble cavitation outside the bucket
  - 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.

Vapor pressure of water for various temperatures

Temperature °C	Vapor Pressure, P_v N/m^2
0	610.8
5	871.8
10	1227.1
15	1704.0
20	2336.9
25	3166.6
30	4241.4
35	5622.2
40	7374.6
45	9582.1
50	12334.8
55	15740.7
60	19917.3
65	25007.0
70	31155.7
75	38549.9
80	47356.3
85	57800.4
90	70107.7
95	84523.5
100	101325.3