NEW DEVELOPMENTS AROUND SHEET AND TIP VORTEX CAVITATION ON SHIPS' PROPELLERS

G.Kuiper
Marin, The Netherlands.

A concept of tip vortex cavitation on propellers is described qualitatively, leading to the distinction of trailing vortices, local tip vortices and leading edge vortices. Improvements of the inception behaviour using this distinction are presented. Observations on developed tip vortex cavitation are given to show that the concept of vortex bursting seems inadequate. The problem of "broadband" vibrations due to a cavitating tip vortex is illustrated. Arguments are given for the fact that a three dimensional approach is necessary to describe shedding of cloud cavitation at the trailing edge of a sheet cavity.

1. Introduction.

New developments are possible when the concepts which are used to describe the phenomena are changing. An example of a changing concept in the field of cavitation inception was the inclusion of viscous effects in the description of cavitation inception. Before that inclusion, cavitation inception had beeen considered from the viewpoint of bubble dynamics only. Although bubble dynamics and boundary layer effects are not yet fully integrated, investigations on cavitation inception have had the same basic background in the last decades.

The problem of inception of tip vortex cavitation is classical and very difficult. It is still important for navy propellers, but progress in this field has been very limited and only some simple empirical scaling relations and a basic two-dimensional modeling is available. CFD can potentially bring the prediction of tip vortex cavitation on a new level, but this is still under development and only for the non-cavitating case. In this field new physical concepts are being developed and in this paper some results are presented.

The behaviour and collapse of a developed tip vortex is increasingly a subject of concern in practice. Here the question is which parameters are important for e.g. rudder erosion and for pressure fluctuations on the hull. One such a parameter is the occurrence of vortex bursting. Good observations, both at model and at full scale, can help to develop an understanding of the phenomena and lead to adequate modeling of the problem. In this paper observations are presented and discussed.

Finally there is the problem of erosion on propellers due to cavitation. Erosion is the final stage of inception, development and collapse of cavitation. Bubble cavitation is generally avoided on ship propellers, so the problem of erosion is most apparent on sheet cavitation. This occurs always in highly dynamic conditions, where shedding of clouds of cavitation occurs at the trailing edge of the sheet cavity. To connect the calculations with impact calculations of a bubble cloud it is necessary to estimate a length scale of these structures. This has not yet been possible, due to the complicated structure of the clouds. The problem is often investigated in a two-dimensional way, e.g. in CFD calculations. In this paper it is argued that this simplification makes that the most important parameter of cloud shedding may be lost.

2. The model of a tip vortex.

Inception of vortex cavitation is still one of the most complex phenomena on a ship propeller. Both nuclei content, probably the total gas content, the strength of the vortex, the size of the viscous core and the vorticity distribution outside the viscous core determine the inception conditions. In this list the vortex is thought of as a predominantly transverse velocity field, so that a two dimensional description can be used. Without cavitation inception the model as described by Rule and Bliss (1992), as shown in Fig. 1, is representative for this approach.

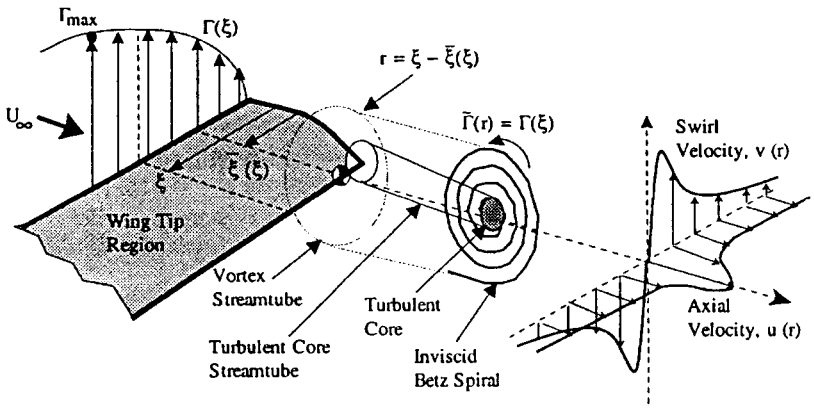


Fig. 1. Vortex model as used by Rule and Bliss(1998)

This model can be summarized as follows. The change in bound circulation on the wing generates trailing vorticity. This vorticity rolls up from the tip. Conservation of circulation and of the first and second moment of vorticity provides enough information to determine the span location and the radius of the trailing vortex at every axial position. Conservation of axial flux of angular momentum leads to the determination of the axial induced velocity. The roll-up process can be considered as taking place on a series of nested, contracting circular tubes. Rule and Bliss show that the axial velocity leads to a stronger singularity in the invicid vortex core than the classical fully two-dimensional approach. The singularity in the core is eliminated by the viscous core, which is taken as a solid body rotation up to a certain radius and connected to the outer flow using a logarithmic velocity distribution. Such a logarithmic velocity distribution is a solution of the fully 2 dimensional Navier-Stokes equations.
It is important to note that Rule and Bliss show with this model that rollup is a three-dimensional process and that an axial velocity is required, which in turn has a significant effect on the roll-up process. The importance of the axial velocity or pressure distribution was already stressed by Batchelor (1964)

3. Determination of tip vortex inception.

Still a cavitating tip vortex is generally modeled as a predominantly two dimensional flow. An example of such a nicely cavitating tip vortex as shown in Fig. 2.

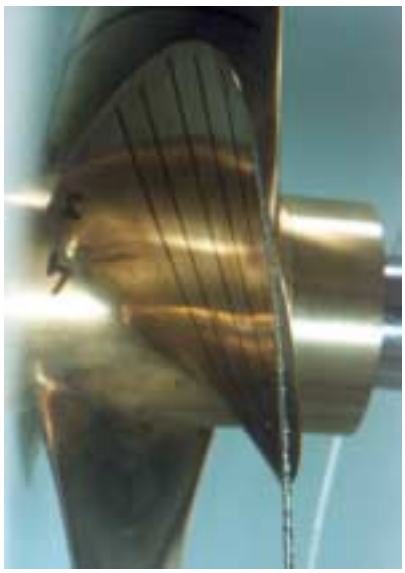


Fig. 2. Cavitating tip vortex

Cavitation occurs in the center of the vortex. This makes it possible to locate the vortex core, but it also shows that cavitation removes the viscous core. Arndt and Keller (1992) have made some exercises with a simple two-dimensional Rankine vortex with a solid cavitating core, showing that two simultaneous solutions are possible, a cavitating and a non cavitating one, for the same vortex strength and angular momentum. Are we looking for something which is undefined when we look for the inception conditions of a vortex? In practice inception occurs in a flashing way. The temporal variation of visual inception of cavitation is generally averaged over time, so that inception is called when e.g. cavitation is visible during 50% of the time. This is very difficult to determine and the percentage is often a very rough estimate. An alternative and better way is to call inception when you see it at least once per unit time. When the time is chosen as e.g. 10 seconds it means that after observation of a cavity it is checked if within 10 seconds the cavity re-appears. If not inception is not yet called.

The observation of Fig.3 shows some discrepancies with the model as described above. The roll-up process predicts an increase in the vortex strength with increasing distance to the tip. In the invicid two dimensional model this would increase the diameter of the cavitating core. It does not, on the contrary, the diameter has the tendency to slowly decrease (Kuiper, 1981). This illustrates that the cavity diameter is not directly related with the total vortex strength of the tip vortex. Some efforts have been made to redefine the inception conditions from the diameter of the cavitating core as a function of the pressure or cavitation index (vanTerwisga et al, 1999). An example is given in Fig.3, in which a_c is the cavitating core radius of the tip vortex and σ is the cavitation index. From two-dimensional models such as described above the relation between the core radius and the pressure can be expressed as a power law. When the power is known, measurements of the core radius versus the pressure can replace inception measurements at very small core radii, where the inception condition may be undefined or very difficult to determine because it depends on Reynolds number and nuclei distribution. It has been found that the cavitating condition is not dependent on those parameters (vanRijsbergen and Kuiper, 1997). The definition of a minimum diameter is sufficient to define the inception condition in Fig. 3 in a repeatable and unique way, independent of the scale!

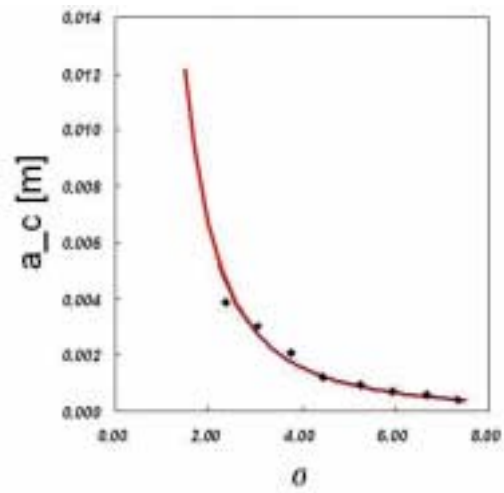


Fig. 3 Cavitating core diameter of a vortex versus pressure coefficient.

The next problem arises when this approach is followed: the determination of the diameter of the cavitating core. In the case of a strong tip vortex in steady conditions the core may be a smooth tube. But this tube is very sensitive to variations in pressure along the core. When e.g. in a cavitation tunnel a "smooth" cavitating vortex core is generated, the actual shape of the cavity is strongly different from a tube with constant diameter. A typical observation is given in Fig. 4. from a high speed video (vanRijsbergen and Kuiper, 1997).

Fig. 4 Cavitating tip vortex.

So it requires a statistical analysis of many pictures to determine the average diameter of the cavitating core of the tip vortex. The disturbances of the cavitating core are probably caused by pressure disturbances in the tunnel. In a non-uniform inflow velocity, such as occur with propellers in a wake, this effect is strongly amplified. This, in combination with the fact that the slope of the curve in Fig. 3 becomes very small when the radius is small makes that this approach for the determination of the inception conditions is not an easy way out. For strong tip vortices, such as behind an elliptic wing, this approach may however be more accurate and repeatable than simple visual observation of inception. Moreover, when it is true that the cavitating vortex is independent of the Reynolds number, this approach is an alternative for the usual scaling of tip vortex inception by the so called McCormick rule:

$$\frac{\sigma_{ship}}{\sigma_{\mathrm{mod}\,el}} = \left(\frac{Rn_{ship}}{Rn_{\mathrm{mod}\,el}}\right)^{0.35}$$

in which the exponent of 0.35 is more or less based on experience.

However, the problem of tip vortex inception on Navy propellers is *not* a problem of a strong tip vortex, as in Fig. 2. The loading of the tip of a Navy propeller in the design condition is close to zero! Cavitation inception occurs when the tip is slightly loaded and unloaded during the revolution of the blade in a wake. This is expressed in the well know inception diagram, in which the pressure is plotted against the propeller loading (Fig. 5).

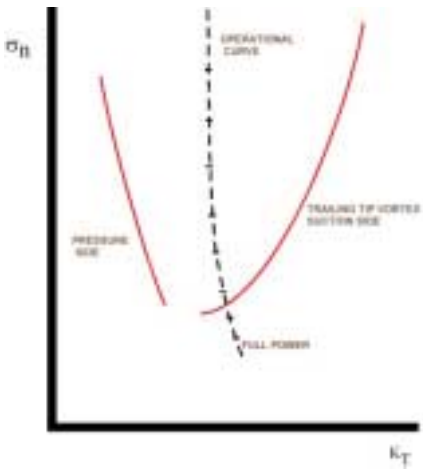


Fig. 5 Inception diagram of the tip vortex of a propeller.

This diagram gives the relation between the inception pressure of the tip vortex on the vertical axis and the propeller loading at the horizontal axis. Because of the shape of the inception curves this diagram is called an inception "bucket". A strong suction side tip vortex occurs in the upper right side if the curve. In this condition the roll-up mechanism is dominant and the description as given above may have some relevance. A strong pressure side vortex will occur in the upper left part of the curve. It is generally assumed that the roll-up model is also applicable in that case.

The operating conditions of the propeller are also indicated in Fig. 5. The intention is that this curve passes through the lowest point of the cavitation bucket. Precisely in this most important region the inception measurements are often very scattered and the inception points at higher pressures(and thus higher positive or negative loading) are used to determine the inception lines by regression. However, the mechanisms involved in inception conditions in the lower part of the bucket, with a very low tip loading, may be different from those at heavier loading. One of the typical differences is e.g. that inception takes place on the tip itself and not in the trailing vortex. Then roll-up of trailing vortices cannot yet be important and other mechanisms have to play a rôle.

4. Types of tip vortices.

Vortex cavitation requires the presence of vorticity. At high loading vorticity is generated at the trailing edge of a propeller blade. At low tip loading separation still occurs close to the tip, while the trailing vortex is much weaker. This results in a typical "local" tip vortex, as is shown in Fig. 6.

Fig. 6 Local tip vortex cavitation

This type of vortex cavitation occurs on the suction side. The tip loading still plays a role, but the location of separation is also very much affected by the tip geometry. Increasing the tip thickness has suppressed the separation at the tip and, up to a limit, this has been successful in suppressing local tip vortex cavitation. Up to a limit, because the increased tip thickness also decreases the local pressure at separation and thus stimulates inception. The thickness/chord ratio in the tip region, as applied nowadays on Navy propellers has therefore increased from some 3 percent to more than 6 percent.

But there is more. An unloaded tip forces the loading towards inner radii, and at these inner radii leading edge separation may occur. This is stimulated strongly by a highly skewed leading edge, which generates a leading edge vortex similar to that of a delta wing. This vortex can be made visible by lowering the pressure. An example is given in Fig. 7.

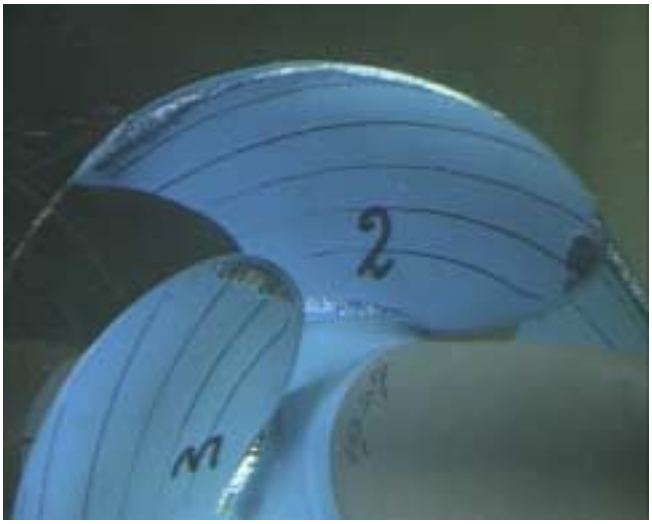


Fig. 7 Combination of local and leading edge tip vortex.

In Fig. 7 the local tip vortex is visible because it cavitates. At the same time a leading edge vortex is visible, at least the cavitating core of it. This leading edge vortex originates at inner radii, where the blade loading is significant and the skew of the leading edge also. Fig. 7 illustrates that the leading edge vortex does not always coincide with the local tip vortex on the propeller blade. Further downstream behind the blade the two co-rotating vortices will merge and become one with the trailing vortex. In case of highly unloaded blade tips the local and the leading edge vortex can have opposite signs. This leads to a very diffuse and sometimes ring-type form of vortex cavitation.

It is important to mention that the leading edge vortex becomes more important when the blade tip is unloaded in the design condition. It can therefore be expected that in the lowest part of the cavitation bucket of Fig. 5 local and leading edge cavitation will dominate over the trailing edge vortex. It is therefore very risky to extrapolate the cavitation bucket towards the lowest point.

The foregoing distinction between trailing, local and leading edge vortex cavitation is necessary because each type of vortex is influenced by different parameters.

The trailing vortex is determined by the radial loading distribution. This has been recognized for a long time and the maximum inception speed of a ship is reached when the tip loading and the radial gradient of the loading distribution are minimal at the tip. The unloading of the tip and especially of the gradient at the tip is restricted, because a too strong unloading of the tip leads to a strong gradient of the loading at inner radii. This leads to a leading edge vortex, which separates inside the blade tip

The local tip vortex is influenced by the tip geometry and application of tip bulbs might improve the performance. There have been many efforts to design a bulbous tip, not many being successful (e.g. Platzer and Souders, 1979). One of the reasons is that the bulb does only work in the lowest part of the bucket. At high tip loading it will mostly have an adverse effect. Many bulbs have been tested on their performance in too high a loading condition.

The leading edge vortex is determined by the vorticity which is produced at the leading edge and transported outward to the tip. In terms of a non-cavitating potential flow calculation, the strength of the vorticity production depends on the adverse pressure gradient near the leading edge. The transport of the vorticity towards the tip depends on the velocity component along the leading edge, and therefore on the skew of the leading edge.

A complicating effect is that the leading edge vorticity may easily be shed from the leading edge at various locations, due to shape variations of the blade. An example of a full scale observation on a frigate propeller is given in Fig. 8, where the vorticity is made visible by cavitation. Not all vorticity generated at the leading edge will end up in the tip, thus complicating the prediction of the strength of the tip vortex.. This phenomenon opens new methods to "distribute" the leading edge tip vortex, e.g. by small variations in the leading edge thickness or by bulbous tip shapes.

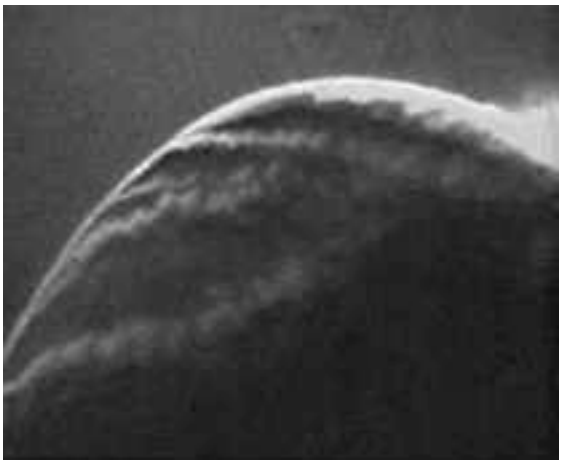


Fig. 8. Shedding of leading edge vorticity inside of the blade tip.

This phenomenon of distributed shedding of the leading edge vortex has also been observed recently on a full scale airplane wing (Brandon et al, 2001). Instead of a single leading edge vortex multiple vortices exist and are shed at various positions on the wing. On ship propellers this

phenomenon persists in strongly cavitating condition, as is shown in Fig. 9, an observation of the propeller of a patrol boat.

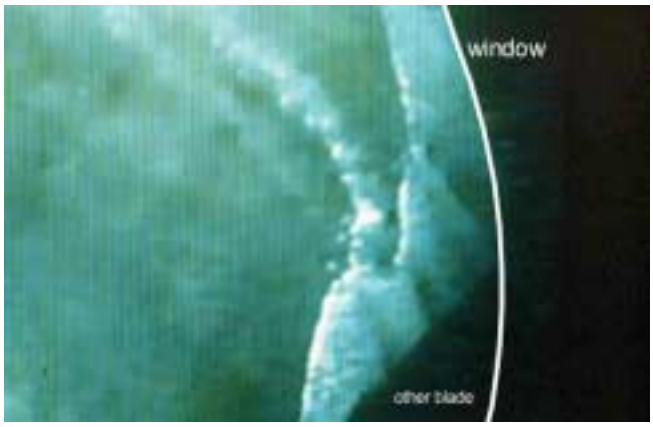


Fig. 9 Trailing edge of sheet cavitation at full scale

The question in Fig. 9 is if the vorticity, which apparently is shed at the trailing edge of the sheet cavity, is related with the leading edge vorticity in non-cavitating conditions. If this is the case the detection of the leading edge vortex at the end of a sheet is possible, even when sheet cavitation is present.

The leading edge vortex is pronounced in the case of pressure side cavitation. In that case the production of vorticity is stronger than on the suction side, because of the camber of the blade sections. Pressure side vortex cavitation is therefore mostly leading edge cavitation. There is a problem in detecting that experimentally, because of the viscous scaling of this vortex. When testing at model scale the lower Reynolds number will delay vortex inception, as in the McCormick rule mentioned above. Sheet cavitation is not delayed by viscous effects. As a result tip vortex cavitation can be overcome by sheet cavitation before being detected at model scale. Consider e.g. the condition in Fig. 10, where a sheet cavity is present in the inception condition of a local tip vortex.

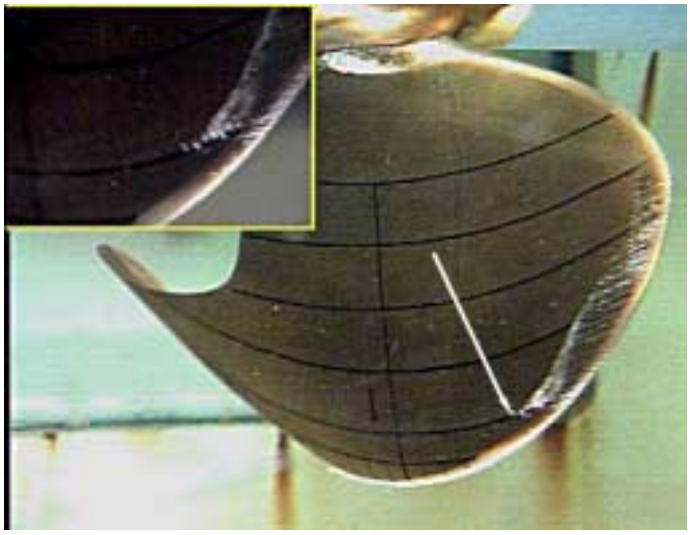


Fig. 10 Inception of a leading edge tip vortex in combination with sheet cavitation.

With decreasing pressure or increasing loading a vortical structure develops gradually near 0.9R. The condition in Fig. 10 is taken as an inception condition, which is when this vortical structure is about to disappear. Here it is assumed that there is indeed a relation between shed vorticity at the trailing edge of the sheet cavity and the leading edge vorticity in non cavitating conditions. Recent correlations with full scale indicate that this is indeed the case.

The reason why the leading edge vortex is not recognized is that it can merge with the local tip vortex, making it invisible because it does not cavitate. It still increases the vorticity at the tip and thus the local tip vortex cavitation. The effect of leading edge vorticity seems more dominant than recognized until now and it is one of the new developments I recognize.

5. Optimizing the inception speed

When the inception speed of a ship has to be improved it is effective to distinguish between the above mentioned types of tip vortex cavitation. As an example a moderately skewed propeller blade has been used as a reference propeller.

5.1 The reference propeller

The contour of this reference propeller is given in Fig. 11a. This propeller was used in a joint research program of the U.S.Navy and the Royal Netherlands Navy.

a. Reference propeller b. Straight leading edge c. Forward skew

Fig.11. Contours of three propellers with varying skew.

A two bladed propeller model was tested in the Marin large cavitation tunnel in open water condition. The inception diagram with the different types of cavitation is given in Fig. 12.

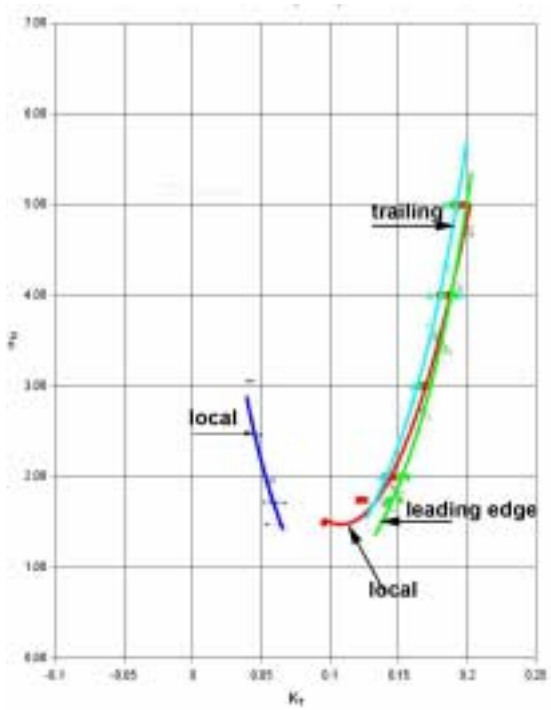


Fig. 12 Inception diagram of reference propeller.

This diagram shows that the reference propeller is a very good one. The inception lines of the various types of tip vortex cavitation are close together, making it difficult to further optimize the suction side inception. Indications are that local tip vortex cavitation controls the depth of the bucket, indicating that a tip bulb might lower the bottom of the bucket. The diagram also shows that the very bottom of the bucket could not be reached in the model experiments due to restrictions in tunnel speed and pressure. These observations were carried out with dual camera's in one blade position of the propeller. This blade position remained the same for other propellers. One camera observed the whole propeller blade, while another was zoomed into the position of expected inception, which had been determined visually beforehand. An observation at inception is given in Fig. 13. At inception of the tip vortex, as shown in the insert, sheet cavitation occurs already at the leading edge, but in this case this does not interfere. The pressure side inception wasa of the leading edge type, similar as in Fig. 10.

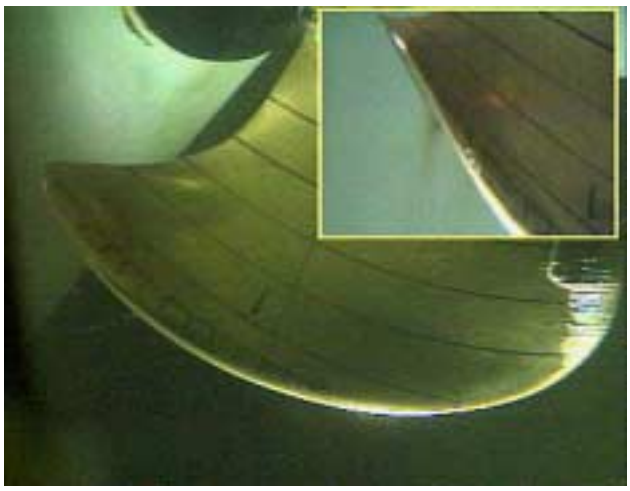


Fig. 13 Inception of local tip vortex cavitation on the parent propeller at σ_n=2.0

It is not always the bottom of the bucket which determines the inception speed of a ship. Variations in the conditions of the ship and the sea make it necessary to have a certain margin against cavitation. The design condition in this case was taken at a cavitation index of 2.0. From Fig.12 it is found that the bucket width of the reference propeller in that condition is 0.09 in K_t.

There are two possibilities to decrease the strength of a leading edge vortex. Decrease the vorticity which is generated at the leading edge and decrease the transport of this vorticity towards the leading edge. When the blade sections are optimized with respect to cavitation inception (the "bucket width" of the blade sections is optimized) there is very little room for change of the pressure peak and the maximum gradients of the pressure over the section. So only the transport of vorticity towards the tip is left. This transport can be changed by the leading edge contour, specifically by the skew of the leading edge.

5.2 The propeller with a straight leading edge

A second propeller blade was therefore designed with a straight leading edge, as shown in Fig. 11b. The radial loading distribution was kept the same as on the reference propeller. The pitch, camber and thickness distribution were designed independently of the parent propeller in order to minimize the bucket width of sheet cavitation and bubble cavitation (Kuiper and Jessup, 1993). A panel code (The MIT code PSF10) was used to calculate the radial loading distribution and the pressure distribution on the blade. The calculations showed that an increase in skew gave a decrease in tip loading when camber and pitch were maintained. The camber and pitch of the blade were therefore adjusted and the blade sections were re-optimized. The control of the tip loading in the calculations was complicated by local singularities on panels close to the trailing edge near the tip. Moreover the program uses a simplified wake model for the trailing vortices, which may lead to an overestimation of the tip loading of the skewed propeller (Moulijn en Kuiper, 1995).

The cavitation bucket of the redesigned propeller with the straight leading edge in open water is given in Fig. 14.

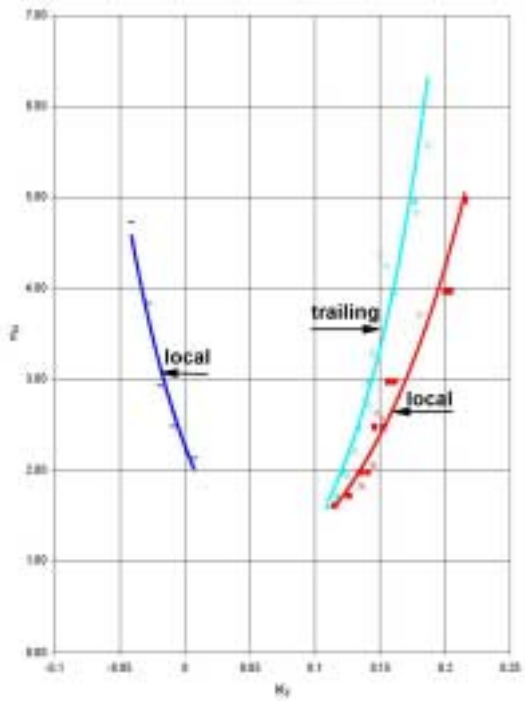


Fig. 14 Inception diagram of propeller with straight leading edge.

At a cavitation index of 0.2 the suction side trailing vortex inception moves from 0.142 to 0.121, indicating that the tip loading increased, although in the calculations these were approximately the same. The numerical singularities in the tip region are the probable cause. The suction side local tip vortex inception is affected less and moves from 0.145 to 0.135. A picture of this condition is given in Fig. 15.

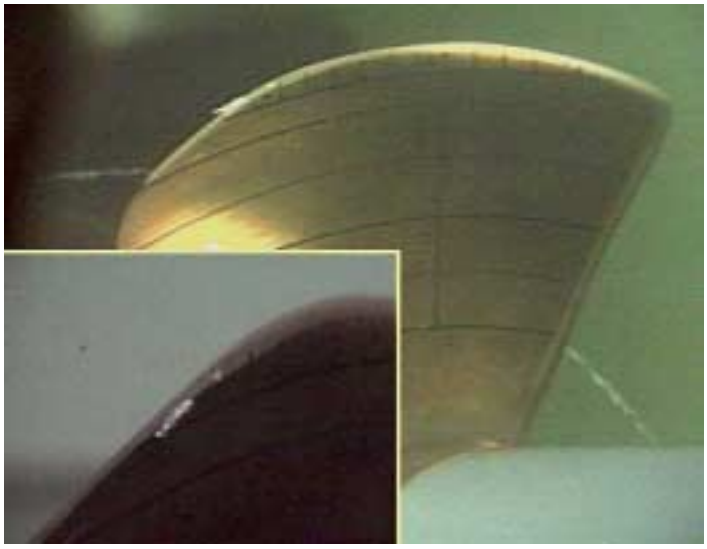


Fig. 15 Local tip vortex inception on the suction side of the propeller with straight leading edge at σ_n=2.0

No leading edge vortex is detected at the suction side. At the pressure side the inception of the tip vortex is a local tip vortex instead of by a leading edge vortex. Pressure side inception is delayed considerably: from K_T=0.052 to 0.007 and the type of incipient vortex is now a local tip vortex instead of a leading edge vortex.

As a result of the shift of the pressure side inception the bucket width of the propeller with the straight leading edge at a cavitation index of 0.2 is increased from 0.09 to 0.114. For the straight leading edge the inception lines at the suction side are further apart than on the parent propeller, indicating that a better balance is possible. To reach this a better control of the tip loading with the panel code is necessary. This will lead to a decrease in camber of at the tip, which will increase the bucket width further.

5.3 The forward skew propeller

A straight leading edge can cause vibration problems when the propeller operates in a wake. Therefore the concept was further extended into a forward skewed propeller, as shown in Fig. 11c. Again the propeller was designed in such a way that the minimum pressure on the blade sections was minimized and the radial loading distribution was maintained. The results are given in Fig. 16.

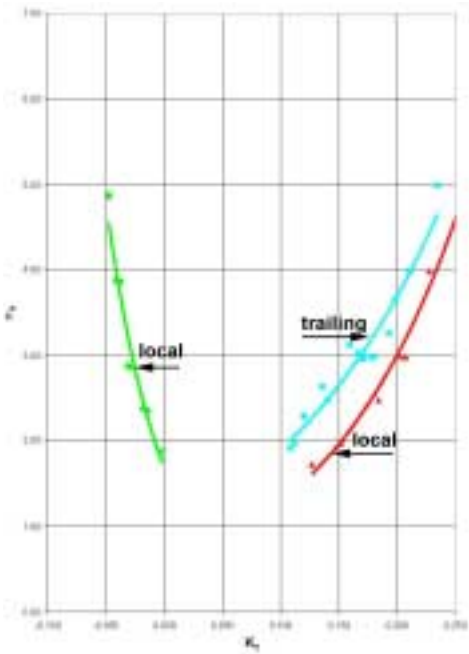


Fig. 16 Inception diagram of propeller with forward skew.

As expected no leading edge vortex is present on either side. At the suction side the trailing vortex dominates rather strongly, indicating that the tip loading can be further optimized, similar as with the straight leading edge. At the pressure side local tip vortex inception occurs, as is given in Fig. 15. There is a substantial amount of sheet cavitation, but the extend is such that it is not expected to influence the blade loading. Local tip vortex inception could easily be identified.

Fig. 17 Local tip vortex inception at the pressure side of the propeller with forward skew at σ_n=2.0

The width of the cavitation bucket of the forward skewed propeller was about the same as that of the straight leading edge. This indicates that once the transport of vorticity towards the tip along the leading is eliminated, no further improvements are reached. A further reduction of the tip loading of the forward skew propeller may further increase the bucket width because of the distance between the inception lines of the trailing and the local tip vortex.

These results show that a distinction between the origin of the tip vortex is effective in increasing the cavitation behaviour of Navy propellers.

6. The appearance of incipient tips vortex cavitation at full scale.

The distinction of several types of vortex cavitation depending on the origin has its consequences for full scale observations also. Trailing edge vortex cavitation is similar at model and full scale, except for the viscous scale effect. Other types of cavitation, especially leading edge vortex cavitation, may have

an appearance which is much like sheet cavitation. There are still questions here if the appearance of full scale cavitation near inception is the same as at model scale. This can be illustrated by the observation of Fig. 8, which at inception will look like a small line of cavitation at the leading edge, attached to the leading edge. Also local tip vortex cavitation can be difficult to distinguish from sheet cavitation. A spot on the tip of a blade, as in the insert of Fig.13, does also occur at full scale, as shown in Fig. 18. Such a cavity spot can only be classified as tip vortex inception by it further development at higher speeds.

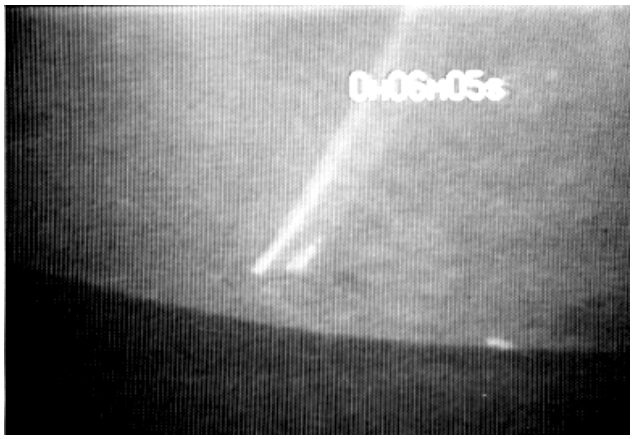


Fig. 18 Cavitation inception of a local tip vortex at full scale.

7. Fully developed tip vortex cavitation.

Fully developed tip vortex cavitation occurs frequently and its importance is increasing because of the requirements to reduce excitations on the hull. These excitations are primarily caused by the dynamic behavior of sheet cavitation. The dynamics of the sheet can be reduced by a higher tip loading, while at the same time the risk of erosion is reduced because the sheet cavity is smoothly connected with the cavitating tip vortex. Two problems occur due to a strongly cavitating tip vortex: rudder erosion and "broadband" excitation of the hull.

7.1 Vortex bursting.

The behavior of fully developed tip vortex cavitation has received relatively little attention. A cavitating tip vortex is supposed to do no harm as it is swept away with the flow. The cavitation will collapse somewhere in the fluid. The precise parameters controlling rudder erosion by a tip vortex is not yet clear, however. In the top region of the propeller plane the cavitating tip vortex often exhibits a "bursting" behavior, as shown in Fig. 19. This phenomenon will be investigated using a series of observations on a Navy oiler with a 5 bladed controllable pitch propeller.

Fig. 19 "Bursting" behavior of a cavitating tip vortex at full scale.
(blade position of the bursting vortex is 90 degrees)

The bursting phenomenon has been blamed for causing erosion as well as for generating pressure fluctuations. The first question is if this is a phenomenon which is related with the well known bursting phenomenon of a vortex. Vortex bursting on e.g. a delta wing has severe effects on the lift of the wing at high angles of attack. A parameter causing vortex bursting is the axial velocity component in the vortex and the mechanism is flow instability. The axial velocity component of a propeller tip vortex is small, however.
Vortex bursting is also effective in decreasing the vortex strength by increasing the viscous dissipation, which is important for the required separation distance of airplanes. In Fig. 19 this seems to be the case, because the cavitation disappears after the burst. However, downstream of a "burst" the cavitating vortex core is often continued without visible weakening of the vortex, as is shown in fig. 20 for the same condition on the same ship in a blade position of 66 degrees against 90 degrees in Fig. 19.

Fig. 20 Vortex "burst" upstream of the rudder.
(blade position of 66 degrees)

So the "burst" exists already before the rudder is approached. It is also remarkable that the location of the "burst" is always steady in space, while bursting of a vortex occurs at a certain distance form the blade tip. This indicates already that the behavior as in Fig. 19 is not the same as vortex bursting.

The parameter causing the "bursting" behavior most probably is the variation in vortex strength over the blade position. When at tip vortex decreases in strength after the blade has passed a wake peak, the diameter of the vortex also decreases in strength. This is illustrated in Fig. 21.

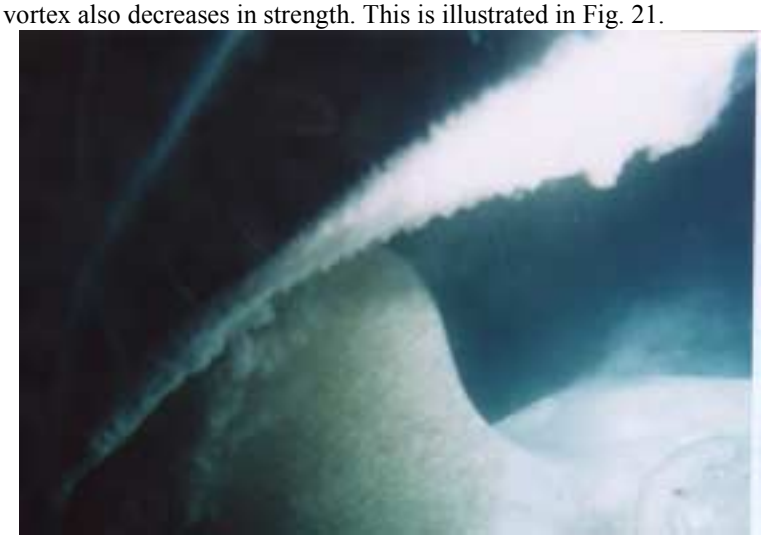


Fig. 21 Decreasing vortex strength with increasing blade position.

The so-called "vortex burst" of a cavitating tip vortex seems therefore caused by load variations of the blade. To avoid confusion it is better to describe this phenomenon e.g. as "blowing up" the vortex instead of vortex bursting. The passage of a blade trough a wake peak leaves behind a vortex with a blown up region, as shown in Fig. 22. Note that the blown up vortex is always more cloudy than the stable cavitating vortex core. What is needed is a model of a tip vortex with variable strength. Since viscous dissipation will be small the change in vorticity may lead to ring vortices perpendicular the the vortex, which are responsible for the cloudy behaviour of the blown up part of the vortex in Figs. 21 and 22

Fig. 22 Blown up vortex core.

7.2 Rudder erosion.

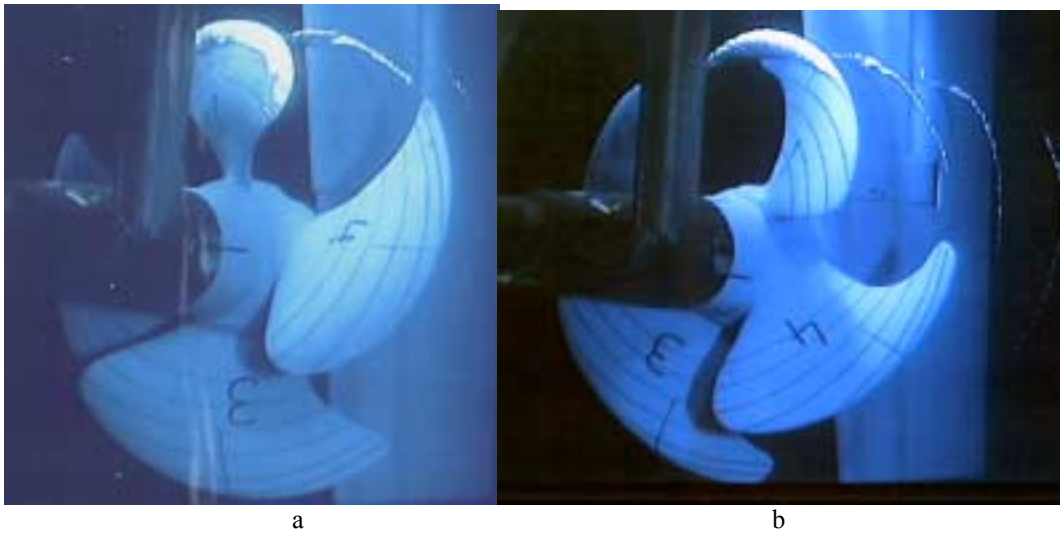
The next question which arises is if the cause of rudder erosion is due to the fact that it is hit by a cavitating tip vortex which is blown up in front of the rudder. Indications are that this is not the case, because not all cases of rudder erosion exhibit such a blown up tip vortex. It seems that a solid cavitating tip vortex core can also erode the rudder.

When the tip vortex hits the rudder it wraps around the leading edge of the rudder. In Fig. 20 this process is just starting. The part around the leading edge collapses on the surface of the rudder, while the cavitating core continues on both sides of the rudder. The cavitation at the side connected with the propeller tip is generally stronger than on the downstream side, as is seen in Fig. 19. A mechanism of erosion could be the implosion of the vortex around the leading edge, since that implosion occurs on the rudder surface. In the case investigated here no erosion was present on the rudder and a reliable prediction of the risk of erosion from observations cannot be given yet. New developments are necessary here to evaluate the risk of erosion due to a cavitating vortex which hits the rudder (or any foil) perpendicularly.

8. Pressure fluctuations due to tip vortex cavitation.

An unexpected consequence of a strongly cavitating tip vortex can be "broadband excitation". The pressure fluctuations generated by a fluctuating sheet cavity are typically in blade frequencies or multiples of it, up to the fourth or fifth blade frequency. This seems to be different in the case of a tip vortex, where apart from these discreet frequencies energy is radiated in all frequencies in that same frequency range. This is often not detected in model tests, because the analysis of the pressure signals on the hull is done by "ensemble averaging" of the signal. The pressure signal is then averaged over a number of revolutions and the averaged signal is further analyzed. This enhances the signal to noise ration of the blade frequencies, but it filters out the other frequencies. To detect "broadband excitation" narrow band analysis of a time registration is necessary.

Fig. 23 is an example of a propeller in behind condition at model scale which generated such broadband excitation.



a b

Fig. 23 Tip vortex cavitation generating broadband excitation.

The amplitudes at blade frequency were low, but the ship vibrated anyhow in frequencies outside the blade frequencies. The narrow band spectrum on a representative pressure pick-up above the propeller at model scale gave a pressure spectrum as given in Fig. 24.

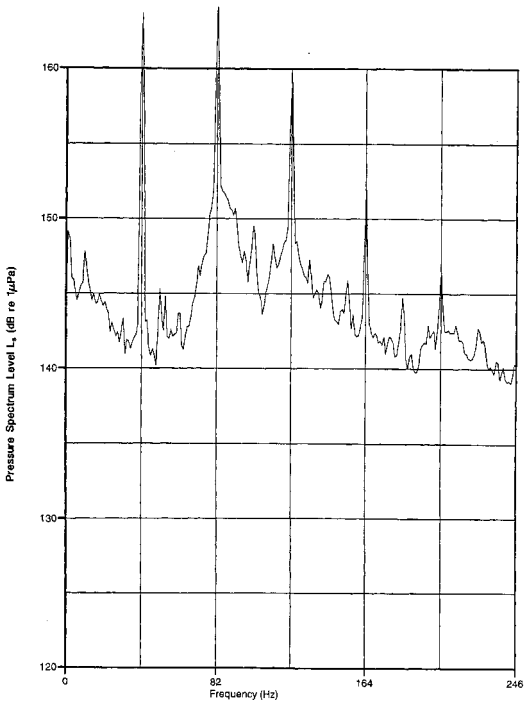


Fig. 24 Spectrum of hull pressure fluctuations

The blade frequencies are still dominating, but there is a significant amount of energy spread out in frequencies in between, especially around the second and third blade harmonic. In this way the construction is always excited in its own frequencies and the vibration level in the ship depends on the damping. For the amplitude of the blade frequencies statistical experience is used to estimate the risk of vibrations. For this broadband energy no comparisons are available. The way to reduce this to acceptable levels was to reduce the tip loading in the top position, thus reducing the strength of the cavitating tip vortex of Fig. 23b. This will increase the amplitudes of the blade harmonics, which are caused by the dynamics of the sheet in Fig. 23a.

These experiences do not yet reveal precisely what the mechanism is which causes the broadband pressure fluctuations. It can be assumed that when the tip vortex becomes strong enough the implosion mechanism is such that a range of frequencies is generated, independent of the blade rate. There is no sign of cloudy break-up at the end of the tip vortex, although single pictures taken with a time lapse observation system cannot give details of the dynamics. The parameters controlling this mechanism of broadband excitation are still unknown and should be investigated further. The result of the lack of knowledge is a hesitation to go to heavily loaded tips, although this would be beneficial for the blade rate excitations and for efficiency.

9. Sheet cavitation.

One of the challenging topics of cavitation research is unsteady sheet cavitation (see the discussion of this topic by Franc in this symposium). For a long time the cavity has been considered as a single valued volume of vapor attached to the surface, which can be calculated by potential flow methods. This requires an artificial closure condition at the trailing edge of the cavity. The work of Kinnas and coworkers explores the possibilities of this approach. The ultimate validation criterion of these calculations is not the cavity extent, as is often used, but the calculated pressure fluctuations. The calculation of the pressure fluctuations is being developed. (Kinnas et al , 1999, Dang, 2001). In his potential calculations Dang modeled a truncated re-entrant jet (Dang and Kuiper, 1998). In three-dimensional flow the precise modeling of the re-entrant jet seems less important for the cavity shape and extent because of the tangential flow along the closure of the cavity.

Potential methods, however, are not able to predict the risk of erosion. Experimental determination of this risk is also extremely difficult or impossible. Visual judgement of the cavitation behavior and paint removal tests are used at present to qualitatively assess the risk of erosion.

The shedding of vaporous clouds by sheet cavitation is a vital element in the chain of events leading to cavitation erosion and this shedding is a topic of investigation. Models exist to describe the implosioon of a spherical vaporous bubble cloud, but the size (diameter) of this cloud should follow from calculations on sheet cavitation. The problem is to find a length scale of the shed cavitation at the trailing edge of a sheet cavity. Again because of restrictions in the calculation methods two-dimensional calculations are dominant. The length scale is then taken as the length between the cavity closure and the location where the re-entrant jet hits the cavity surface. However, when shedding of cavitation is observed it is never two-dimensional. Even when the cavity length in global terms seems constant along the span of a foil (Fig. 25) the local mechanism is always highly three dimensional.

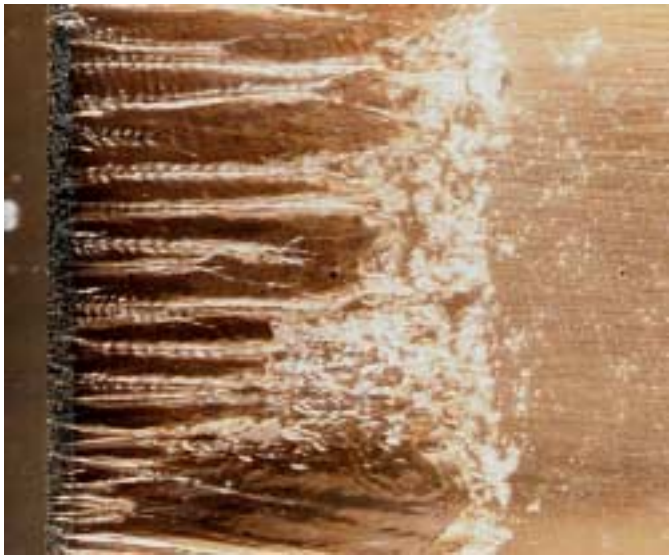


Fig. 25 "Two-dimensional" sheet cavitation on a foil.

Whenever a cavity closure is smooth there is a significant re-entrant jet which exits at another location of the foil or of the blade. An example of such a stable closure on a model propeller is given in Fig. 26.

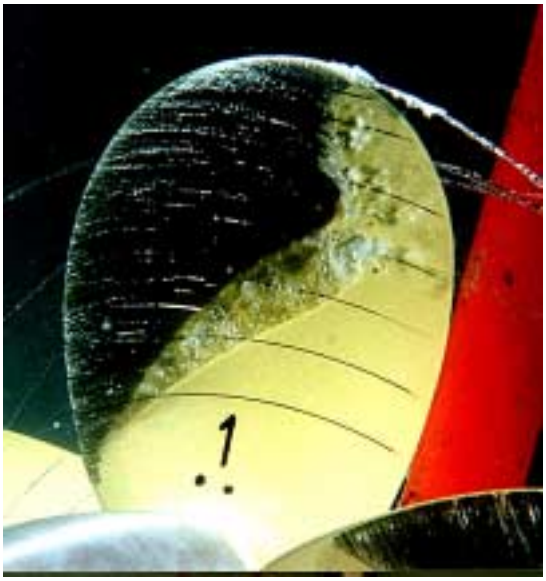


Fig. 26 Stable and cloudy closure of sheet cavitation on a propeller blade.

Whenever the re-entrant flow reaches the cavity closure, a strongly three-dimensional shedding occurs. When the shedding is coherent over some length of the cavity closure, vortical structures are generated, as in Fig. 27.

Fig. 27 Vortical structures at cavity closure

However, as is also seen in Fig. 26, the cloudy structure is in general not dominated by large scale vortices.

The mechanism generating these shed structures is the re-entrant jet. However, because of the fact that the trailing edge is always ragged and highly three-dimensional, the jet at a local scale, is never plane but always converging or diverging. When the jet is diverging a smooth part occurs, as in Fig. 27 upstream of the shed vortex. When the jet is converging the fluid in the cavity is concentrated, reaching the upper surface of the cavity much earlier than in a two-dimensional case. Schoon (2000) paid some attention to this phenomenon in his thesis, and it may be crucial in understanding the shedding phenomena of cavitation. This can be illustrated by high speed observations of a sheet cavity on a propeller in a wake. The cavity surface is transparent until streaks occur at seemingly random locations on the cavity (28). The assumption is that this is caused by local convergence of the re-entrant flow.

Fig. 28 Streaks on a sheet cavity prior to breakup of the sheet.

The collapse of the cavity seems to be strongly related to the streaks which occur on the surface of the sheet. Since the re-entrant jet always "reflects" against the trailing edge of the cavity, the contour of the sheet cavity determines the convergence of the re-entrant jet. This would mean that the length scale of the of the disturbances along the trailing edge of the cavity are more important than the length of the two-dimensional re-entrant jet in flow direction.

Fig. 27 is an example of an effort to generate a cavity which can be used for modeling the process and for validation of calculations. It is a profile with variable angle of attack over the span. The variable angle of attack over the span makes it possible to generate a prescribed shape of the cavity. (This approach is possible due to the availability of numerical milling machines). Investigations of the inner structure of sheet cavitation with various trailing edge contours will be investigated to find the parameters controlling the shedding and formation of clouds.

The inner structure of sheet cavitation is very dynamic. A collapsing sheet cavity produces a very strong re-entrant jet, which can spoil not only the cavity, but also the tip vortex. An example of the latter is given in Fig. 29, where the tip vortex is torn apart by the re-entrant flow of the collapsing sheet cavity. This is very common on ship propellers and part of the complicated structure of the tip vortex downstream of a blade is due to this phenomenon. It illustrates that knowledge of sheet cavitation cannot remain restricted to its outer surface.

Fig. 29 Tip vortex destruction by re-entrant flow in the sheet

Acknowledgements

The two bladed propeller designs and their results were part of the TIPVOR program of the U.S.Navy and the Royal Netherlands Navy. Permission to use these results is gratefully acknowledged. The

observations on tip vortex cavitation in front of a rudder were carried out for the Royal Netherlands Navy.

REFERENCES.

ARNDT, R.E.A.,KELLER, A.P., 1992, "*Water Quality Effects on Cavitation Inception in a Trailing Vortex*", J. FLUIDS ENG., VOL.114, PP430

BATCHELOR, G.K.,1964, "*Axial Flow in Trailing Line Vortices*", J.F.M.(1964) VOL.20 P.4 PP. 645-658.

BRANDON, J.M., HALLISSY, J.B., BROWN, P.W., LAMAR, J.E., 2001*, "In-Flight Flow Visualisation- Results of the F-106B with a Vortex Flap*", Symposium on Advanced Flow Management, NATO RTO, Loen, Norway.

DANG, J., 2001, "Numerical Simulation of Unsteady Partial Cavity Flows", PhD Thesis Delft University of Technology, The Netherlands.

DANG, JIE., KUIPER, G., 1998, "Re-entrant Jet Modelling of Partial Cavity Flow on Two Dimensional Hydrofoils", 3rd Int. Symposium on Cavitation, Grenoble/ JFE Vol. 121,dec. 1999

DANG, JIE., KUIPER G., 1998, *"Re-entrant Jet Modelling of Partial Cavity Flow on Three Dimensional Hydrofoils*", ASME FED Summer Meeting, Washington D.C./JFE Vol 121.

KINNAS, S., CHOI, J.-K., KOSAL, E., YOUNG, J., LEE, H., 1999*, "An integrated computational technique for the design of propellers with specified constraints on Cavitation Extent and Hull Pressure Fluctuations* ", Proceedings CFD99 _The international CFD conference.

KUIPER, G., 1981, "*Cavitation Inception on Ship Propeller Models*", PhD.Thesis, Delft Univ.of Technology, The Netherlands.

KUIPER, G., JESSUP, S.D., 1993, "*A Propeller Design Method for Unsteady Conditions*", SNAME Centennial Meeting, New York.

PLATZER, G.P., SOUDERS, W.G., 1979, "*Tip Vortex Cavitation Delay with Application to Marine Lifting Surfaces*", DTNSRDC REP. 79/051

RULE, J.A., BLISS, D.B., 1998*, "Prediction of Viscous Trailing Vortex Structure from Basic Loading Parameters*", AIAA Journal Vol.36, pp208-218.

RIJSBERGEN, M.X. VAN, KUIPER, G., 1997, "*Modeling a Cavitating Vortex*", ASME Fluids Eng. Division Summer Meeting, FEDSM97,Vancouver.

SCHOON, JOHANNES, 2000, "*A Method for the Study of Unsteady Cavitation*", Thesis Chalmers University Goteborg.

TERWISGA, T. VAN, KUIPER, G., VAN RIJSBERGEN, M.X., 1999*, "On Experimental Techniques for the Determination of Tip Vortex Cavitation* ", ASME/JSME Fluids Engineering Summer Meeting, San Francisco.

.