Ship Hydrodynamics, Ship Propeller Acoustics and Cavitation.

Updated 2025-12-05 §4 cavitation and cavitation inception, pages 9 and 10

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Content

Tags: acoustics, cavitation, cavitation inception, education, marine propeller, naval architecture, inception nuclei, ship hydrodynamics, testing facilities

1 Introduction.

Before a new built ship is transferred to the operator test trials will be run at high sea to find out whether the new ship complies with the specifications. For example: verify the contracted speed power by speed trials.
One of the prominent issues is cavitation on the propulsion system: the ship propeller. Cavitation cannot always be prevented so you want to control it by design.
The designer and shipbuilder have made predictions of the type and amount of cavitation. This is usually tested at model scale in a testing facility like MARIN(www.marin.nl) .
At the end of the day the type and intensity of cavitation must be tested at high sea to find out whether reality is within the margin of the allowable predictions.
Below some videos are shown of so-called high sea testing. The videos are recorded from a view through a window in the stern of the top of the propeller. Vortex cavitation is shown.
Click on the link. A video of full-scale cavitation: A side view of the propeller through a window in the stern of the ship. Dimensions: a propeller with a diameter of about 6 m.
https://videos.files.wordpress.com/ljl0SvG5/full-scale11_fmt1.ogv
or, on Youtube,
full scale 11 fmt: https://youtu.be/-tMrAZvaK9E
A view from above of the same propeller. Part of the rudder is shown.
https://videos.files.wordpress.com/d1yY8F8a/full-scale1_fmt1.ogv
or, on Youtube
full-scale1-1.mpg: https://youtu.be/JxuDj8lIP0s

Cavitation observation such as shown in these videos are conducted already for several decades. These observations are essential to find out about noise and dynamic pressures produced by the cavitating propeller and whether a particular type of cavitation creates erosion of the propeller. Nowadays to make observations, windows in the stern are no longer necessary. By means of a small hole in the hull the observations can be made. Here another example of full-scale cavitation is shown:

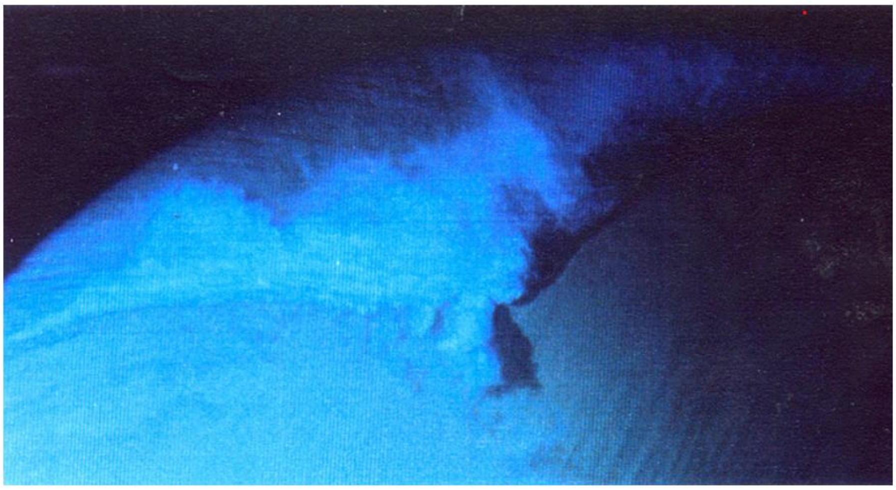

Figure 1 Development of detached cavitation on the propeller of a containership full scale

First and for all a model of the propeller is evaluated on laboratory scale. This can be done in a so-called cavitation tunnel and/ or a depressurized towing tank. First and for all, to perform model testing scaling laws need to be fulfilled. Think of Reynolds number, cavitation number and Froude number similarity.

2 The Cavitation Tunnel.

Let us take a closer look at cavitation.

Cavitation can be categorized schematically into:

- Sheet cavitation.
- Bubble cavitation and
- Vortex cavitation.

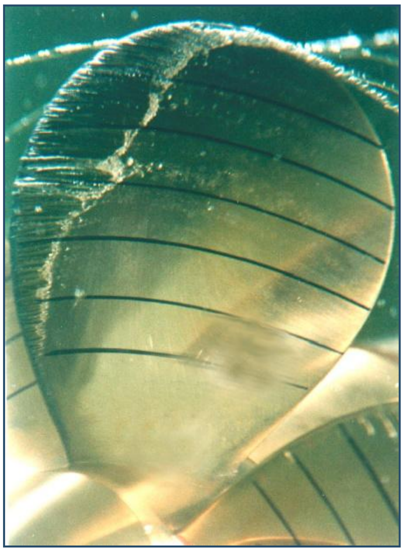

Figure 2 Sheet Cavitation

Here a typical example of sheet cavitation is shown. The model propeller shown is specially designed for this type of cavitation. Some tip vortex cavitation is visible.

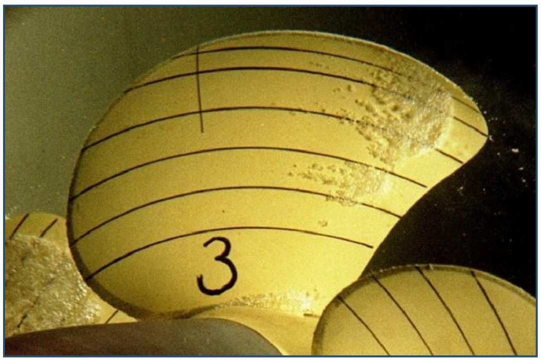

Figure 3 Bubble Cavitation

This model propeller shows bubble cavitation, special designed for this type of cavitation.

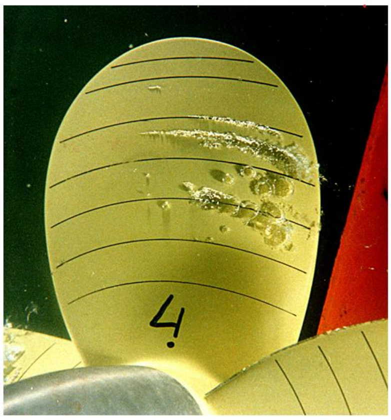

Figure 4 Another example of bubble cavitation

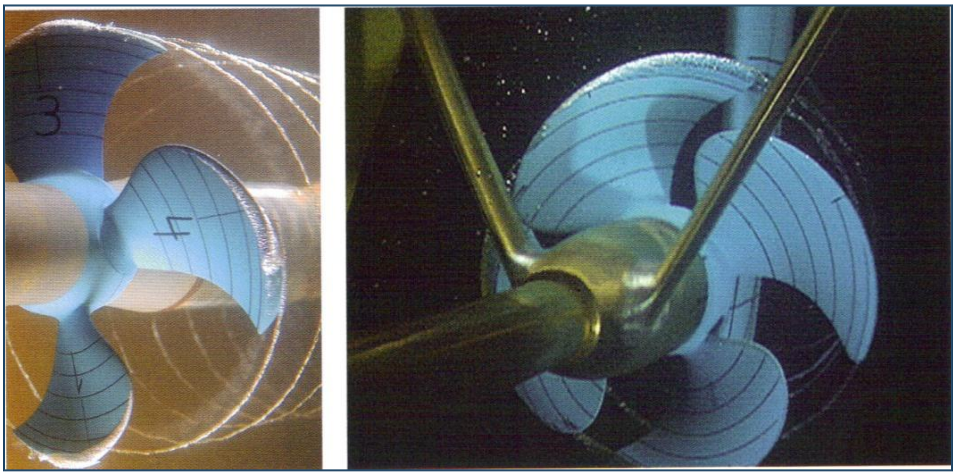

Figure 5Tip Vortex Cavitation

The above model propeller displays vortex cavitation.

No examples of supercavitating are shown here. With supercavitating the sheet cavity on the propeller blade stretches in chord wise direction beyond the trailing edge of the propeller blade.

Research in testing facilities is aimed to design a propeller showing allowable cavitation on full scale. To conduct test in a meaningful way test must be done under full scale conditions. This condition can only partially be fulfilled. I come to that later.

In the old days model test where don in the open air. Then the conditions to test cavitation are not correctly scaled. To this end a cavitation tunnel is used.

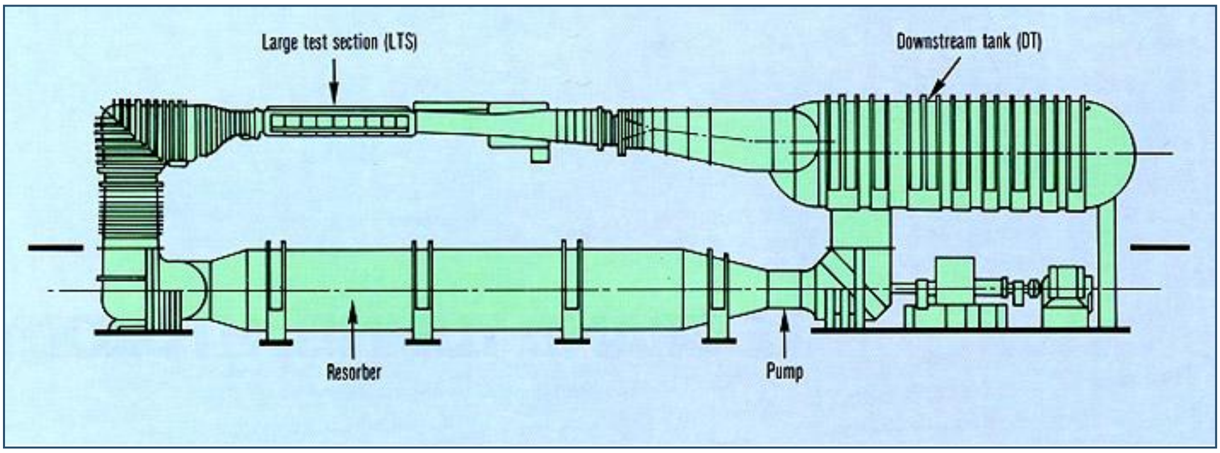

Figure 6 Cavitation Tunnel

In the above picture a cavitation tunnel is shown. This is a closed circuit in which the water flow and pressure can be varied. Cavitation tunnels are used to study in detail cavitation on propeller models. This type of facility has created a considerable insight in cavitation erosion.

Through clicking on the link below some observations in a cavitation tunnel are show: first a hydrofoil model for basic research and then a couple of videos of a cavitating propeller.

https://videos.files.wordpress.com/zNmSjgMl/part2_fmt1.ogv

or, on Youtube,
part 2 fmt: https://youtu.be/jSM-Z_eIWOM

Below a schematic representation of a cavitating propeller on Youtube
HoodMovie.avi: https://youtu.be/MyQgO7JFaos

Cavitation inception research is extensively reported in Kuiper (1981, 2012).

3 The Depressurized Towing Tank.

However, it is not just erosion. What has also to be evaluated are the vibrations induced on the ship's hull by the dynamic behaviour of cavitation. To this end a Depressurized Towing Tank has been developed in the Netherlands by MARIN. The tank is schematically shown below.

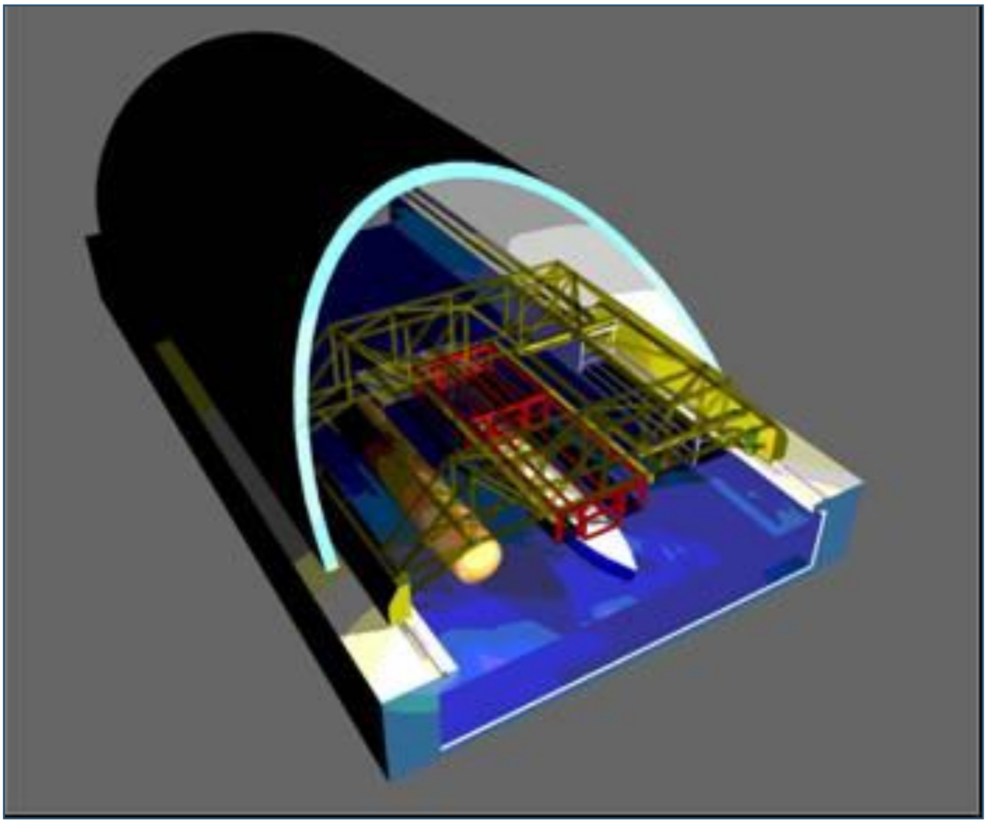

Figure 7 Schematic View of the inside of the Depressurized Towing Tank

The ship model is displayed below the red structure. Model with a length of 12 meters can be evaluated. The width of the tank is 18 meters, the length is about 240 meters, and the

height is 8 meters. The pressure can be lowered by a factor of 40.
To give you an idea about the size an aerial picture of the Depressurized Towing Tank is shown below. Look at the automobiles, for comparison, and the yellow ship models with a length of about 12-14 m.

Figure 8 An Aerial View of the Depressurized Towing Tank

In this testing facility a completely scaled model can be evaluated with the cavitating propeller included. A video of the propeller can be observed by clicking on the link:

https://videos.files.wordpress.com/soMgu7bA/model_fmt1.ogv
or, on Youtube,
Model fmt 1: https://youtu.be/IBckHNMk-tI

The recording has been made from inside the ship model.

However, not all the hydrodynamical scaling rules are complied with. This was one of the reasons to construct a testing facility as the Depressurized Towing Tank shown above. With such a facility there is compliance with two hydrodynamical parameters: the Froude number and the cavitation index. In this way predictions for prototype flow, i.e., full scale, have been improved. However, Reynolds number similarity is not obtained.
Nevertheless, experienced testers are able to predict rather accurately on basis of the test results the performance of the ship in full-scale. This is supported by a lot of data created with full scale testing and trials.

4 Cavitation and Cavitation Inception.

Cavitation basically is a non-stationary process resulting into erosion of the propeller and a magnified pressure level in the vicinity and far field. This results into vibrations of the hull and higher noise levels. Consequently, inception of cavitation is a subject of significant importance to propeller design. In Kuiper (1981) a broad overview is presented.
Inception is strongly influenced by nuclei, e.g., tiny gas bubbles and/or particulate matter in the water. First and for all, the testing must be done under correct scaling conditions, i.e., the cavitation number. In the Appendix, some basic information on cavitation is presented. This correct scaling can be obtained by lowering the ambient pressure in the Towing Tank: Depressurized Towing Tank.
As mentioned, nuclei can influence cavitation inception. This is important in a circulating water tunnel (Bernd, 1973) as well as in experiments without moving water like a towing tank (Noordzij 1976). Bubbles and particulate matter will disappear over time in such testing facilities. Consequently, cavitation inception is delayed. So, something must be done there. For the simple reason, that at full scale there are always bubbles and particulate matter in the water.
To simulate reality, additional seeding of tiny bubbles is applied in model testing. Use have been made of additional seeding of tiny gas bubbles by means of electrolysis.

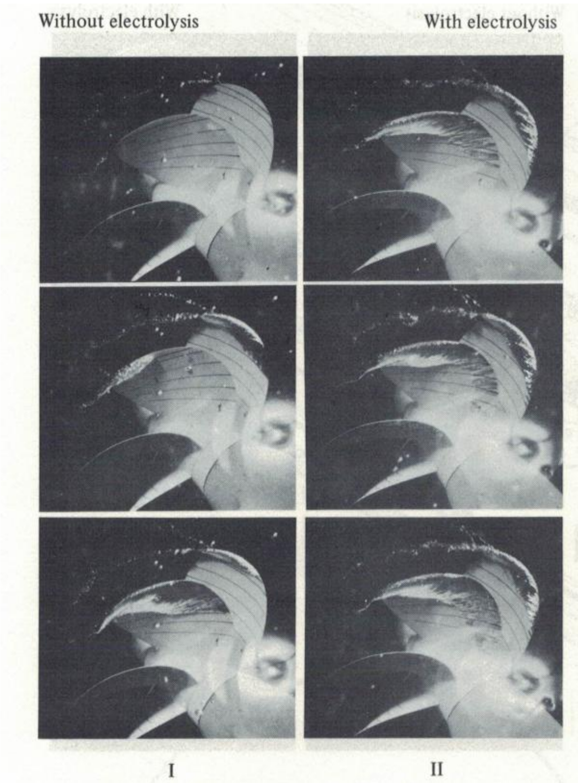

Figure 9 Cavitation observations in the Depressurized Towing Tank

As shown in Figure 9, the results of this seeding are presented. The above results of seeding of tiny bubbles are promising. The stabilizing effect of additional bubbles is clearly demonstrated.
In Fig. 10 the experimental setup is shown. To give an idea about the dimensions: the two electrolysis wires (anode and cathode) are 0.01 m apart, the propeller diameter is about 0.4 m, and the width of the towing tank is about 18 m. The small hydrogen and oxygen bubbles

are transported by the flow into the propeller plane.

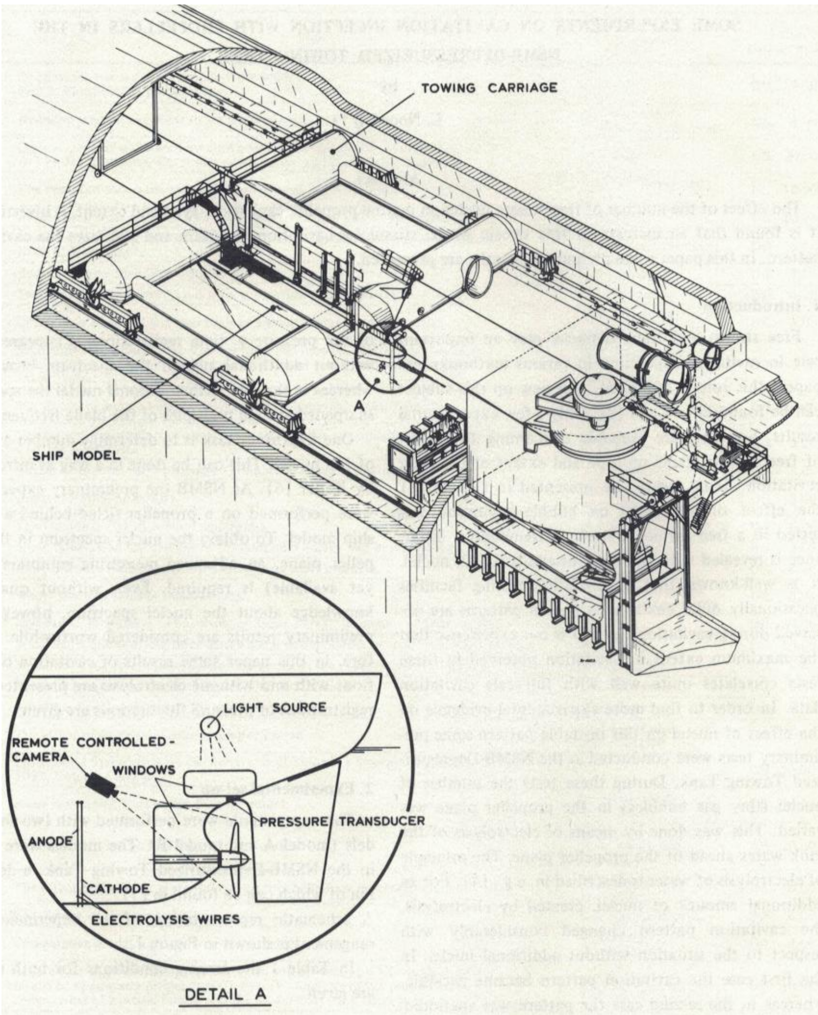

Figure 10 Schematic representation of the experimental set-up

Remark: the seeding of the small bubbles is not optimized with respect to:
- the position of the wires on the model hull,
- the diameter of the wires and consequently the diameters of the bubbles.

In Boshuisen and Versmissen, a review is presented of the cavitation observation techniques as used in the Depressurized Towing Tank shown in Figure 10. Especially, the time dependent behavior of cavitation has been paid special attention. This is done by means of synchronization techniques based on the propeller rotational frequency. Some techniques used are:
- High-speed camera, about 10^4 frames per second to determine time dependent behavior.
- Stereophotogrammetry to determine the thickness distribution of the cavity on a propeller blade.

To execute these measurements, the model to be used should be prepared in such a way the cavitation can be observed from inside the model. See also Figure 10.

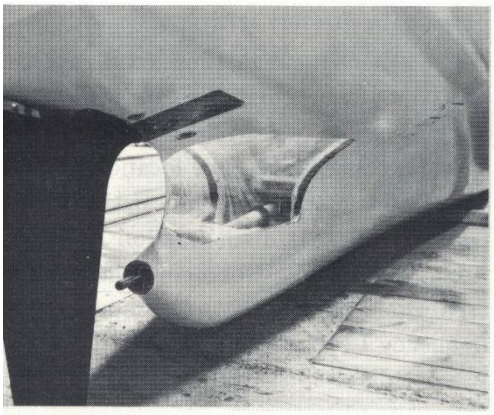

Figure 11 Model with perspex windows in the stern of the model

To this end perspex windows are built into the stern of the ship model, Figure 11. This window is below the waterline. In this way refraction is prevented.

Due to the results of the cavitation observations, you want to know the size and number of nuclei. Keller (1973) developed an optical technique for determining the nuclei spectra. Like Bernd, Keller concluded the number and size of the nuclei in water are dependent on the history of the water and on its content of contaminating particles.
To increase the knowledge of the effect of nuclei measurements of size and number of these nuclei are necessary. Nuclei spectra measurements in the depressurized Towing Tank are reported by Noordzij and Cruijff.
Keller concluded cavitation inception to be strongly affected by the nuclei content. This is of particular interest when a critical level for inception of a nuclei spectrum under prototype circumstances could be indicated. Then the critical level for testing facilities can be calculated and set. Since knowing the critical prototype spectrum, a critical level for model testing can be meaningfully hypothesised. What could such a hypothesis look like?
The hypothesis is: to obtain equal cavitation inception susceptibility for both prototype (full scale) as well as laboratory flow, the encounter frequency with nuclei must be the same for both types of flow. (Nota bene: Kuiper mentioned encounter frequency in *Cavitation in Ship Propulsion.* Kuiper dealt basically with dynamics of the cavitation nucleus: a tiny gas bubble). This will result in an expression for the number density of the nuclei, be it particulate or tiny bubbles, as a function of the scaling parameter λ. Let the number density, i.e., the number of nuclei per m^3 say, to be n.
A typical distance separating the nuclei is:

$$\Lambda = n^{-1/3}. \qquad (1)$$

Then, a so-called encounter frequency for the propeller and the nuclei can be defined as

$$\frac{V}{\Lambda}, \qquad (2)$$

where V is a typical velocity of the propeller of the propeller blade tip, $\omega D/2$ say. Here ω is the angular frequency and D the diameter of the propeller.
Now let us define the dimensionless frequency $No = \frac{V}{\omega\Lambda} = \frac{D}{2\Lambda}$. (3)
Then the basic assumption is this number No to be scale invariant. So:

$No = (\frac{D}{\Lambda})_m = (\frac{D}{\Lambda})_{fs}$, (4)

where subscripts m, fs denote model and full scale, respectively.

With model scale $\frac{D_m}{D_{fs}} = \frac{1}{\lambda}$, where λ is of order 10, (4) can be written as

$(\frac{1}{\Lambda})_m = \lambda(\frac{1}{\Lambda})_{fs}$. (5)

Usually for model testing Froude number *Fr* is a constant:

$Fr = \frac{\omega D/2}{\sqrt{D/2}} = \omega(\frac{D}{2})^{1/2} \rightarrow [\omega(\lambda)^{1/2}]_{fs} = [\omega]_m$. (6)

Now, we have all the ingredients with *Fr* to be a constant number.

Plugging (1) into (5) we obtain:

$n_m = \lambda^3 n_{fs}$. (7)

So this No number is telling us the nuclei density in laboratory testing need to be much larger than in prototype flow/full scale flow.

Knowing the nuclei density at full scale give you an idea about the number of bubbles to produce in laboratory testing. To find out about the threshold for cavitation inception on model scale you need to know the threshold at full scale. Hence, you need full scale data on inception bubbles for cavitation inception at full scale. Well, that is not easy to say the least. So, to interpret the results shown in Figure 7, you need a range of experiments with n_m ,i.e., bubble seeding. In this way knowledge is developed about n_m and the stability of the cavitation pattern. Correlation with measurements in a cavitation tunnel is helpful.

The best way to proceed is comparison of the full-scale cavitation pattern with the testing results of the full-scale model with various positions of the electrolysis wires on the model hull. Furthermore the amperage of the electrolysis can be varied (Kuiper, 1981).

As stated by Acosta: “*The bubble seeding method has real merit when the bubble distribution of the prototype flow (full scale) as well as that of the laboratory flow is known.*” (Noordzij and Cruijff). Well, to find out about the bubble distribution in laboratory flow is not a fundamental problem. For prototype flow it is.

5 Design and testing of marine propellers.

Geopolitics plays a special role in the world of marine propellers. Navy surface vessels have been surveyed by submarines for more than 100 years. Nowadays (2020) submarines play an ever-increasing role in see bound strategies of the superpowers. Detecting submarines is an ever-interesting issue.

Detecting submarines has been done by sensors measuring the noise produced by the submarines. Noise created on-board by the diesel-electric powering system and noise created out-board by the flow around the submarine. One of the main sources of this flow noise is created by the propeller.

We will focus on the hydrodynamics of the propeller. A non-cavitating propeller creates noise generated by the turbulent flow around the propeller. This noise is amplified when the propeller starts to cavitate. In the fore going sections several types of cavitation are shown. Every type has its acoustic fingerprint. Consequently, propeller design is a major tool in reducing noise produced by the propeller (Noordzij, et al). The main conclusion of this research is bubble cavitation is an extremely loud type of cavitation. Tip vortex cavitation

and sheet cavitation produces approximately the same noise level. The difference between bubble cavitation and sheet/tip vortex cavitation is of the order of 10 -20 db.
As mentioned before, to optimize a propeller design testing on a certain model scale and CFD are important tools. To make meaningful predictions with help of model scale testing there are certain conditions for such a testing facility. For example, to make reliable predictions about the far-field hydro-acoustics of a cavitating propeller precautions are needed. Furthermore, the addition of nuclei has a significant effect on the sound pressure level. This can be attributed to a more stable cavitation pattern. Such a dependence on cavitation inception nuclei necessitates hydro-acoustic testing being carried out in nuclei-controlled water. To evaluate these tests, one must determine number and size of the nuclei in the propeller plane (Noordzij, et al).
Two testing facilities for hydro-acoustic testing on model scale are mentioned in the fore going sections: a cavitation tunnel and the Depressurized Towing tank. Noordzij and Van der Kooij, concluded for propeller diameters used in cavitation testing of about 0.3 m, at 1.5 m from the propeller, the far-field noise spectrum can be determined with an accuracy of 2dB.

6 Special topics.

In The Economist section on Science and Technology (January 21st, 2017) a particular example of supercavitating is discussed. It is about a submerged weapon: a kind of torpedo. Super cavitation is taken advantage of to reduce the resistance of the torpedo. Due to super cavitation the torpedo has an extremely low hydrodynamic resistance.

7 Literature.

Bernd, L. H., *Gas Nuclei, Surface Films and Turbulent Dissolving as Related to Cavitation Inception*, Proceedings, IUTAM Symposium Non-Steady Flow of Water at High Speeds Leningrad 1971, (ed. L.I. Sedov and G. Y. Stepanov), Moscow, Nauka, 1973.

Boshuisen, D.C. and A.G.P. Versmissen, *Cavitation Observation Techniques in the NSMB Depressurized Towing Tank,* Int. Shipbuilding Progress, March 1978.

Keller, A. p., *The Influence of the Cavitation Nuclei Spectrum on Cavitation Inception. Investigated with a scattered light counting method.* Proceedings, IUTAM Symposium Non-Steady Flow of Water at High Speeds Leningrad 1971, (ed. L.I. Sedov and G. Y. Stepanov), Moscow, Nauka, 1973.

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Noordzij, L., *Some Experiments on Cavitation Inception with Propellers in the NSMB-Depressurized Towing Tank*, Journal of International Shipbuilding Progress, Vol. 23, 1976.

Noordzij, L., Cruijff, H. J., *Introductory nuclei spectra measurements in the NMSB-Depressurized Towing Tank,* Journal of International Shipbuilding Progress, Vol. 25, 1978.

Noordzij, L., Van Oossanen, P. and A. M. Stuurman, *Radiated Noise of Cavitating Propellers*, Proceedings, Symposium on Noise and Fluid Engineering, ASME Winter Annual Meeting, Atlanta, Georgia, Dec. 1977.

Noordzij, L., Van der Kooij, J., Hydro- Acoustics of a Cavitating Screw Propeller; Far-Field Approximations, Journal of Ship Research, Vol. 25, June 1981, pp. 90-94.

The Economist, Science and Technology, Torpedo Junction, January 21st, 2017.

Appendix On Cavitation Phenomena and Consequences

Cavitation basics

- Cavitation number $\sigma = \dfrac{p_0 - p_v}{\frac{1}{2}\rho V^2}$
- Pressure coefficient $C_p = \dfrac{p - p_0}{\frac{1}{2}\rho V^2}$

The cavitation number, σ, is mentioned in the text.
p_0 the ambient pressure at large distance,
p_v the vapour pressure,
C_p the coefficient describing the pressure distribution, p , on the propeller blade,
V a typical velocity of the propeller blade.
Type/form of cavitation, more detailed than presented in the text:

Which form does it take

- bubble cavitation
- sheet cavitation
- blade root cavitation
- vortex cavitation
- Propeller Hull Vortex (PHV) cavitation
- hub vortex cavitation

Bubble cavitation on a foil

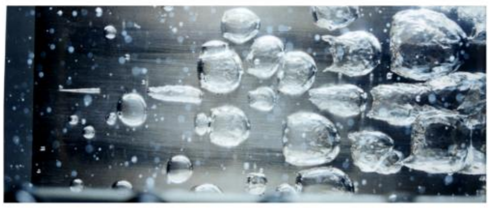

Figure 12 Bubble cavitation on a foil evaluated in the cavitation tunnel

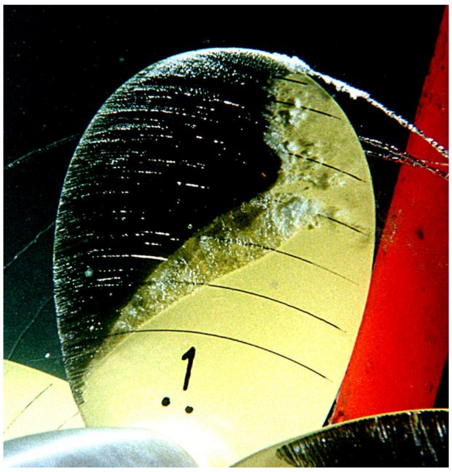

Figure 13 Sheet cavitation with unloaded tip of the propeller

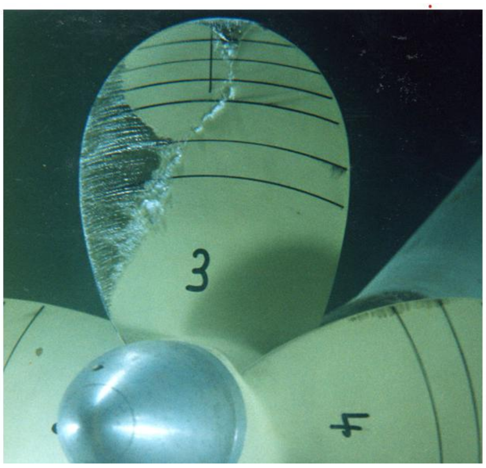

Figure 14 Imploding sheet cavity on propeller blade

Summary of adverse effects of cavitation:

- Cavitation erosion
  - especially ferocious: cloud cavitation, pressure side cavitation, possibly bubble cavitation
- Vibrations through pressure fluctuations
- Radiated noise
- Thrust breakdown

The effects of cavitation on erosion of the propeller blades is also shown in the text.

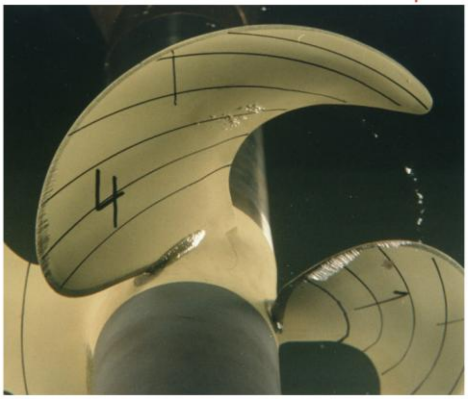

Figure 15 Propeller blade root cavitation

Types of Vortex Cavitation:

- Trailing vortex cavitation
- Local Tip Vortex cavitation
- Leading Edge Vortex cavitation
- Propeller Hull Vortex (PHV) cavitation
- Hub Vortex cavitation

Pictures of vortex cavitation next page.

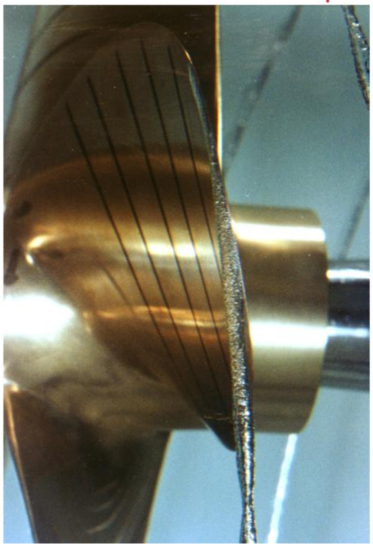

Figure 16 Tip Vortex Cavitation

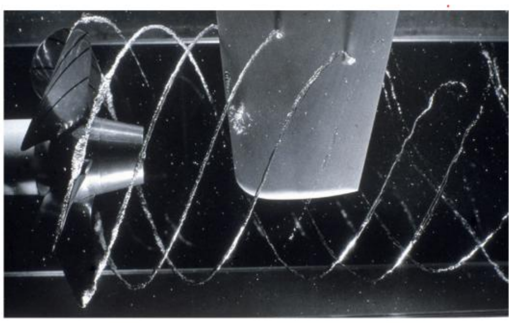

Figure 17 Developed Tip Vortex Cavitation

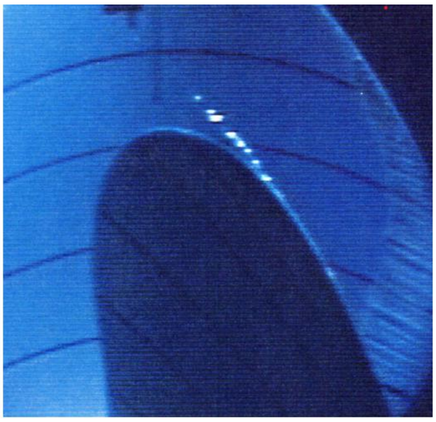

Figure 18 Tip Vortex Inception

Figure 19 Full Scale Observation

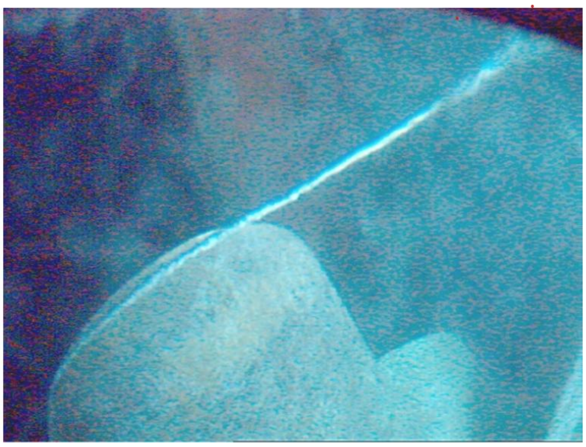

Figure 20 Full Scale Observation

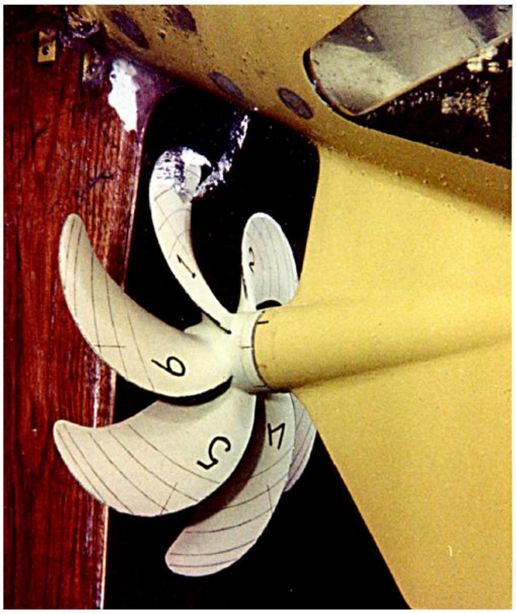

Figure 21 Propeller Hull Vortex Cavitation Model Scale

Part of the perspex observation window is shown. The dark spots in the stern are the positions of the pressure transducers.

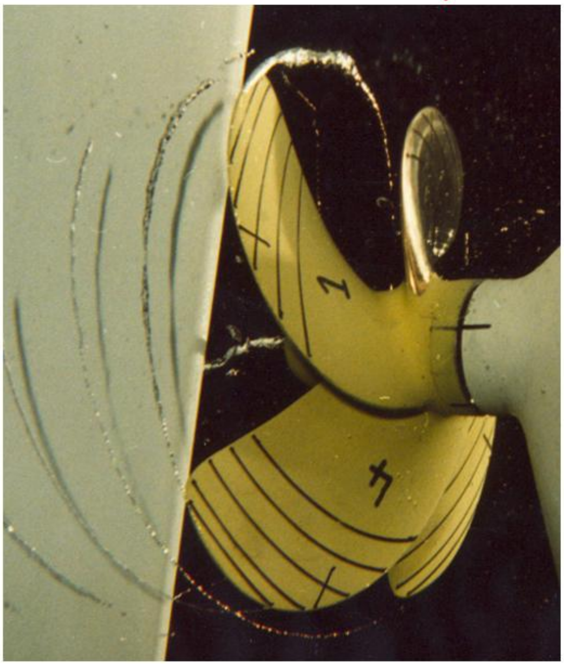

Figure 22 Propeller Hub(axes) Vortex Cavitation Model Scale

We conclude this appendix with the adverse effect of cavitation on erosion, Figure 23.

Figure 23 Erosion due to cavitation Full scale

The adverse effect of erosion of a propeller blade is crystal clear, to say the least. The propeller blade is almost perforated and showed a sort of destruction of the propeller blade. An extreme example.
Another adverse effect of cavitation is vibration of the ship due to pressure fluctuations of imploding cavities. Sometimes the effect of pressure fluctuations on the hull is such that the ship needs to cruise and reduced speed with considerable commercial impact.
Figure 24 a schematic presentation of a propeller blade and the pressure distribution on the hull with and without cavitation, next page.

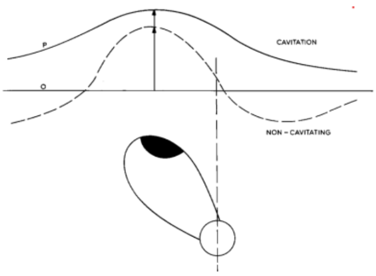

Figure 24 Schematic presentation of the pressure fluctuations on the hull due to a cavitating propeller

In Figure 25 the pressure fluctuations on the hull of a ship model are presented. The dashed curve represent reduced cavitation due to a lack of inception nuclei. This is corrected by seeding additional nuclei via electrolysis. In this way a more realistic full scale cavitation pattern is obtained. Amplitude is plotted for full scale circumstances. This resulted into an increase of about a factor 2 in the amplitude of the spectrum.

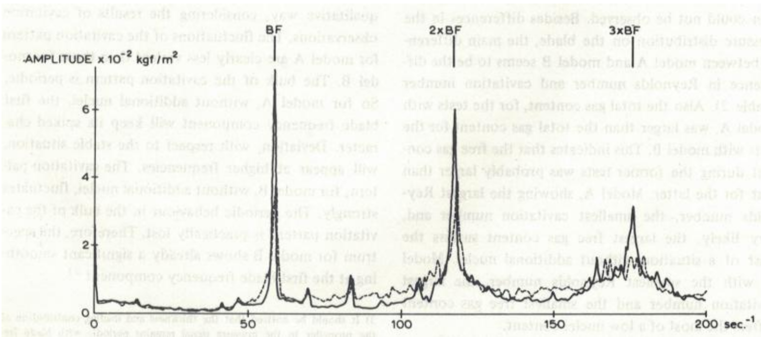

Figure 25 Amplitude spectrum of the pressure versus time registrations on a ship model

Both adverse effects show the need for advanced propeller design.

Below, sheet cavitation of a ducted propeller on model scale is presented.