On the History of Propeller Cavitation and Cavitation Tunnels

E.-A. Weitendorf
Consultant, formerly Hamburg Ship Model Basin, Hamburg, Germany
e.a.weitendorf@t-online.de

Abstract
A condensed survey on the history of propeller cavitation and its understanding as well the development of cavitation tunnels is given. Propeller cavitation effects ship performance by thrust breakdown, erosion, vibration and noise. Each of these detrimental consequences will be shortly dealt with. Following the similarity laws for cavitation, a limited number of full scale investigations on propellers will be looked at which form one basis for the cavitation and propeller excited pressure fluctuation correlation between model and full scale.

1. Introduction

At the end of the nineteenth century difficulties with ship propellers occurred**:** Projected higher ship speeds could not be achieved. In 1894 the British torpedo-boat destroyer "Daring" reached merely 24 instead of 27 kn. Only the enlargement of the screw area by 45% secured success. This was based on Barnaby's view of a given boundary for the propeller speed, or a given maximum tensile strength of the water, at which a break down of the propeller inflow occurs. It corresponds to a thrust per projected screw area of 11¼ lbs/inch² in case of the "Daring", as Thornycroft proposed (Barnaby 1897). Following a proposal by R.E. Froude (Thornycroft and Barnaby 1895) the phenomenon of this harmful propeller behavior was called "Cavitation" derived from the Latin word "cavus,-a, -um"(*Engl.* "hollow").

The originally frustrating test series with the "Turbinia" began in 1894 (Parsons 1897). After seven different types of screws and then in 1895 with three on one shaft, the disappointing speed of only 19¾ kn was attained. Only after many deliberations, also on the phenomenon cavitation and tests with hot water in a saucepan and in the first small cavitation tunnel, the forerunner of nowadays tunnels, finally in April 1897 with three screws on each of three shafts the top speed of 32¾ kn was achieved. Burrill (1951) in a Memorial Lecture described Parsons' ingenious engineers achievement based on until then not published original documents. After Parsons was first focused on the phenomenon in connection with "the racing of the screw ... [and] ... loss in propulsion effect" he later, from about 1910, worked on "the effects of cavitation ... in another form, namely erosion and pitting of the blades ..." (Burrill 1951). This early extension of Parsons' work shows that the cavitation phenomenon is widely spread. A full description of the cavitation problem, as for e.g. by Eisenberg (1953), or Young (1989), is seldom possible. Therefore, only some - of course arbitrarily selected - aspects of the propeller cavitation problem can be dealt with in the following.

2. Cavitation Phenomenon, its Effects, and Aspects of its Physical Background

The first photographs of propeller cavitation (Figures 1a, 1b) were taken in Parsons' first cavitation tunnel. When about 1911 the photograph in Figure 1b was published it was even for experts like D. W. Taylor not clear whether cavitation would occur at the back or face side of the screw. Yet, Barnaby (1911, p. 225) stated "... most clearly that the cavities are at the back of the blade. (See Fig. 2, Plate 31.[Shown here as Figure 1b])".

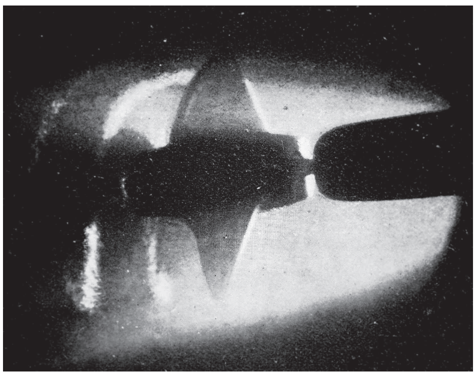


Figure 1a. One of the first propeller cavitation photographs from Parsons first tunnel (1895) - Propeller Diameter 2 in.; revolution 1500 rpm; acc. to Burrill (1951)

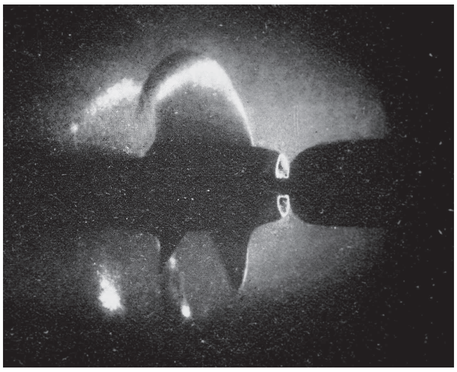
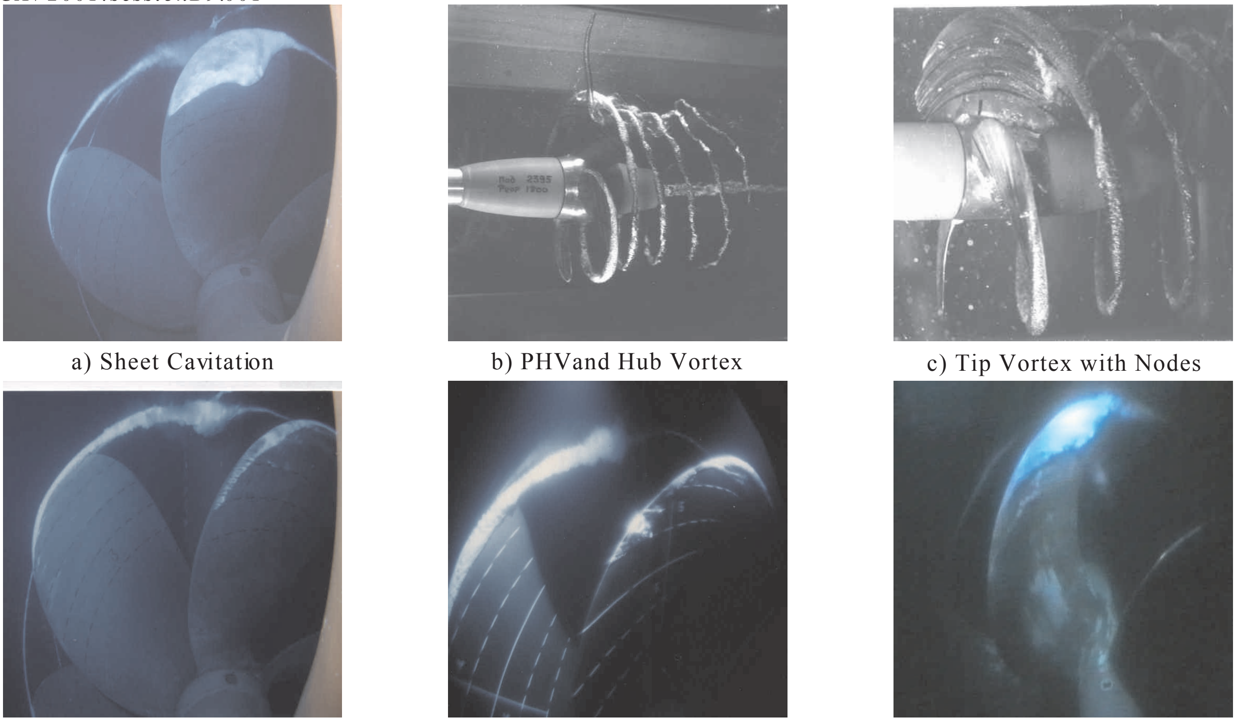


Figure 1b. One of the first propeller cavitation photographs from Parsons first tunnel (1895) – Cavitation at the back of the blade acc. to Barnaby (1911)

Nowadays stroboscopic photographs of propeller cavitation are given in Figure 2. In Figure 2a pronounced sheet cavitation and a thin tip vortex from the "Sydney Express" full scale propeller (Weitendorf /Keller 1978), and in Figures 2b to 2f different types of vortex cavitation are shown. The sheet cavitation is unsteady and excites vibration at the



a) Sheet Cavitation b) PHVand Hub Vortex c) Tip Vortex with Nodes

d) Bursting Tip Vortex e) Cloud Cavitation f) Cloud Cavitation

Figure 2. Different cavitation types of nowadays propellers

ship's hull due to its volume variation. Figure 2b reveals two types of cavitation: an upwards directed hollow vortex, called propeller hull vortex PHV (Huse 1972; Sato et al. 1986) and a hub vortex in the center. The hollow PH V may hit adjacent boundaries and causes irregular vibrations. But this happens only for slow propeller inflows. Figure 2c shows a rather thick cavitating tip vortex with nodes detected by Weitendorf (1973) and in Figure 2d vortex breakdown is shown in front of the rudder, made aware of by English (1979). Further, vortex cavitation partly connected to sheet cavitation occurs at the leading edge of modern high skew propellers (Figures 2e and 2f). All types of vortex cavitation when occurring with volume variation result in vibrations of higher orders. - Finally, cloud cavitation has to be mentioned that is detectable around the bursting tip vortex in Figure 2a and at the leading edge in 2e as well below the massive vortex cavitation in 2f. Cloud cavitation (Emerson 1972, Bark 1998) can be the origin for noise and erosion.

Barnaby's view on the onset of cavitation by trespassing a certain maximum tensile strength of the water is still valid. The beginning of cavitation was already predicted by Euler (1754), he said : "But when it should happen that this quantity [the absolute pressure] will be negative somewhere inside the pipe, then the water would desert the inner wall of the pipe and create a void space ... ." Almost 150 years, up to the problems with the "Daring" and "Turbinia", Euler's prediction remained unnoticed. As correct Barnaby's view on the physical background of the cavitation ever was, his and other general criteria as thrust per screw area (see Lerbs 1936) did not contribute to the elucidation of the problem. Between about 1908 and 1924 detailed knowledge on the cavitation onset was collected by basic investigations, e.g. by tests with Venturi nozzles (Föttinger 1932), pressure measurements on circular arc and aerofoils (Ackeret 1930, Walchner 1932). The pressure measurements on five different profiles by Ackeret (1930) showed that for cavitating conditions there is a linear proportionality between on one hand the difference of static head minus vapor pressure and on the other the dynamic head of the inflow. These measurements on the foils and simultaneous cavitation observations lead to the result that cavitation inception at the profile occurs when the sum out of static head p_0 and maximum suction pressure $(-p_{min})$ is equal to the vapor pressure p_v for given temperature. The condition of the surrounding is determined by the nondimensional number

$$\sigma_i = \frac{p_0 - p_v}{\frac{\rho}{2} V^2} = \frac{p_{atm} + \rho g h - p_v}{\frac{\rho}{2} V^2}$$

with p_v, the vapor pressure for given temperature, p_0 the static head, p_{atm} the atmospheric pressure, h the submergence and V the velocity.

The negative pressure coefficient depends on the profile :

$$-c_{pmin} = \frac{p_0 - p_{\min}}{\frac{\rho}{2}V^2}$$

with $-p_{min}$ the maximum suction pressure at the profile. Thus cavitation occurs for $\sigma_i = - c_{pmin}$. The cavitation number σ as general parameter for cavitating flows was introduced into cavitation problems for the first time obviously by Thoma (1925) who applied similarity considerations on the pressure drop of water turbines.

To determine the water quality at cavitation inception one may (additional to the dissolved air content) either test the reaction of water on a given minimum pressure $-p_{min}$ or try to determine the number of micro bubbles as base for the cavitation process and simultaneously estimate the influence of solid particles as well of pore nuclei. Keller (e.g. 1994) relies on measuring the reaction of the water while Weitendorf and Tanger (1999) tried to ascertain the micro bubbles (by Phase Doppler Anemometer PDA) as cavitation nuclei and also counted the solid particles in their water tunnels.

3. On the Development of Cavitation Test Facilities for Ship Model Propellers

Parsons first tunnel from 1895 (Figure 3) contained almost all components of a modern cavitation tunnel, except the impeller for water circulation. A turning mirror was used for stroboscopic photographs of the propeller with 2 in. diameter. An arc lamp was used for heating the tunnel water. The atmospheric pressure inside the tunnel was removed by an air pump.

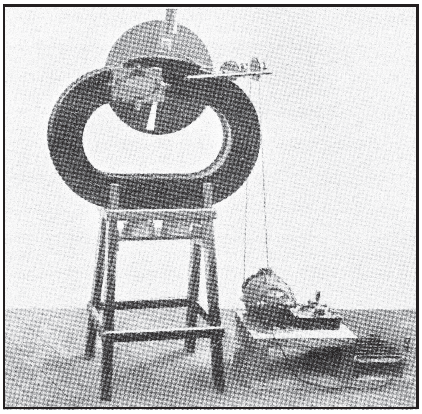


Figure 3. Parsons first cavitation tunnel (1895)

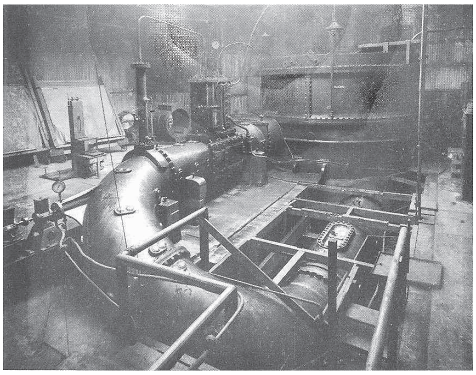


Figure 4. Parsons larger cavitation tunnel (1910)

This tunnel tremendously contributed to the first clarification of the cavitation problem as Figures 1a and 1b show. In 1910 Parsons built a second, a larger, 66 feet long tunnel having a 36 in. diameter of the main circular piping (Figure 4). For removing the bubbles the tunnel had a large settling tank of 14 feet in diameter and 11 ft. and 6 in. high. This tunnel can be regarded as forerunner of British and American tunnels with “resorbers”.

Ackeret’s experimental investigation in Göttingen 1930 was carried out in a similar, smaller tunnel like Parsons second one. In 1927 Lerbs began to develop a propeller cavitation tunnel by carrying out model tests for the tunnel (Lerbs 1931; Kempf/Lerbs 1932). This tunnel (Figure 5) coming into operation in 1931 is the forerunner of some conventional closed-jet cavitation tunnels. Erosion problems at the propellers of the passenger liner ”Bremen” (Figure 13) were the reason for Lerbs’ tunnel. After some improvements of his first tunnel, e.g. a smoother turn behind the test section (Lerbs 1944), Lerbs began in 1939 to construct a larger tunnel (test section of 2.4 m by 1.2 m) for complete models of twin or triple screw navy ships (Figure 6). This “unique facility” (Schade 1946) that never came into operation in Hamburg is now located at Haslar (UK). Figure 6 shows the tunnel during installation in Hamburg 1941.

Examples for the development of cavitation tunnels in the US during the thirties are given in Figure 7a. The US Experimental Model Basin (DTMB) tunnel is described by Saunders (1930), the MIT tunnel by Lewis (1939). The fist tunnel is of a straight forward design that later when transferred from Washington DC to Carderock MD obviously was modified, the second one is remarkable concerning its novel turning vanes.

The British tunnel activities after the “Parsons’ era”comprised the Lithgow tunnel (NPL No 1) from 1932, NPL Tunnel No 2, 1959 (Silverleaf/Berry 1964), and the King’s College Cavitation (later Emerson)Tunnel from 1950 (Atlar 2000). The unusual concept of the U-shaped NPL No 2 Water Tunnel with a resorber of 180 ft depth was based on an analysis of the resorption of bubbles up to 0.3 mm in diameter at all test section pressures and a speed of 13.7 m/s. The total air content of the water could be varied between 4 cc of air and at least 24 cc air per liter (Silverleaf/Berry 1962).

US activities after World War II for research facilities at the David Taylor Model Basin (DTMB) are shown here for example by the 36 in. water tunnel (Brownell/Miller 1964). The tunnel (Figure 7b) has two interchangeable test sections, an open-jet and a closed-jet one, and its resorber can be bypassed.