Advanced Propulsion System
GEM 423E

Week 13: Supercavitating Propellers

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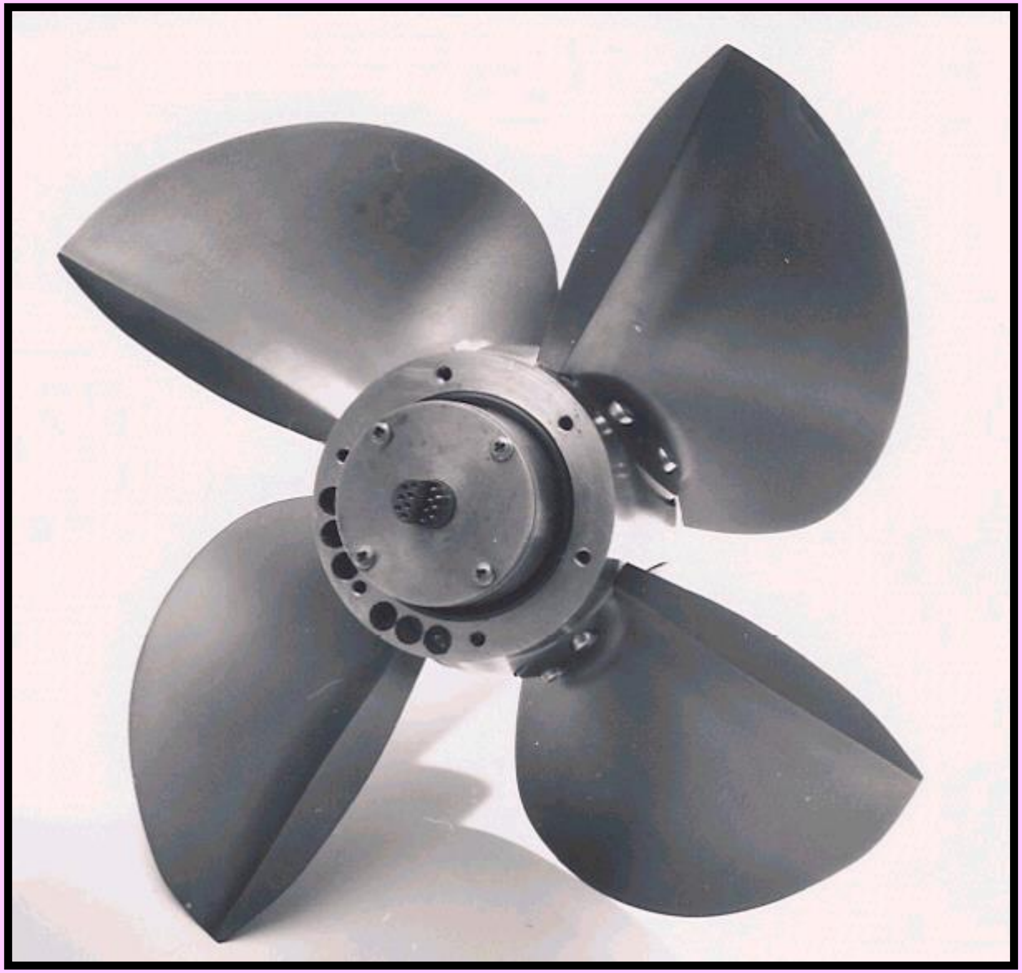


Contents

What is CAVITATION?

The appearance of vapour bubbles and pockets inside an initially homogeneous liquid medium, occurs in very different situations.

Another Definition for Cavitation

- "Cavitation is the breaking of a liquid medium under excessive stresses."
- That definition makes cavitation relevant to the field and methods of continuum mechanics.
- It is convenient for cases in which the liquid is either still of flowing.

An Example for Still Liquids

- A solid body with sharp edges a disk, for example is suddenly accelerated by a shock in still water.
- Bubbles can appear at the very first instants in the region neighbouring the edges, when the velocity of the liquid particulates are still negligible.

An Example of Flowing Liquids

- Flow in venturis or in narrow passages valves for hydraulic control.
- Flow near the upper-side of a wing or a propeller blade.

The Vapour Pressure

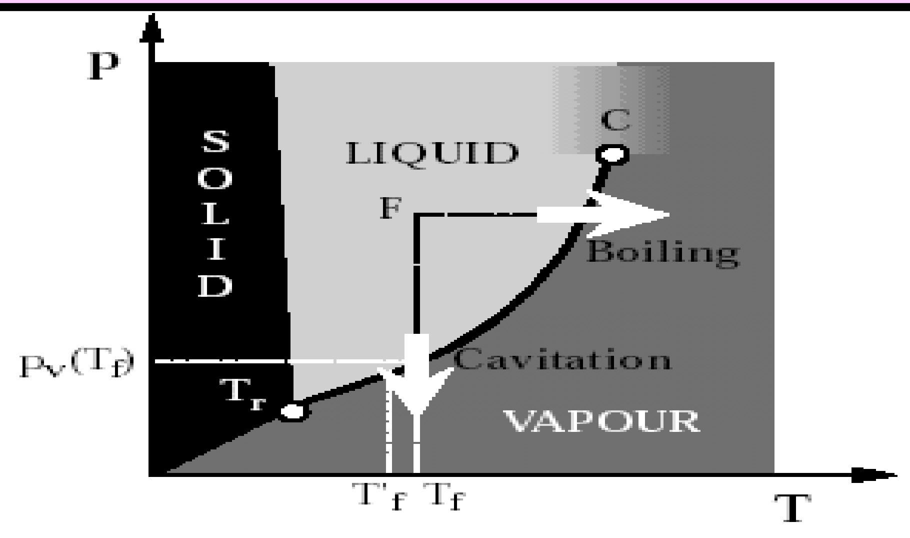


Fig. 2. Diagram for phase changes

Andrews-Isotherms

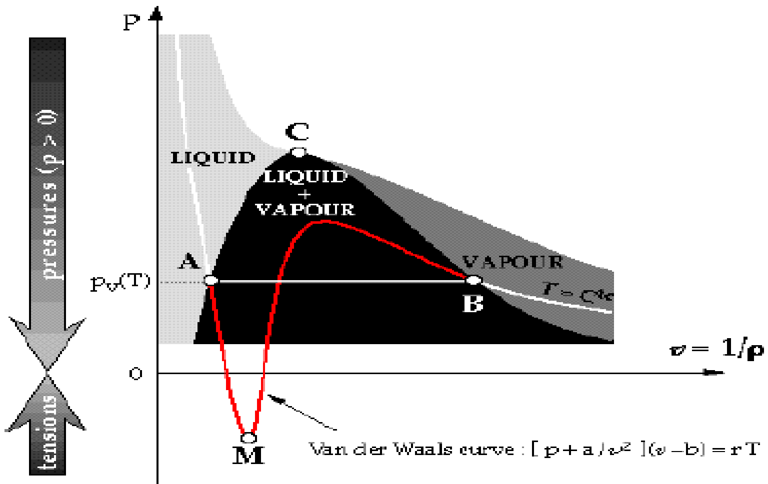


Fig. 3. Andrews-isotherms

Specific Features of Cavitating Flows

1. Pressure and Pressure Gradients
2. Thermal Effects
3. Some Typical Orders of Magnitude
4. The Liquid-Vapour Interfaces

Some Historical Aspects

- The word “cavitation” appeared in England at the end of the 19. century.
- Before, it seems that the problem of the behaviour of liquids in rotating machinery was suspected by Torricelli then Euler and Newton.

- In the middle of the 19. century, The Belgian chemist Donny and the French physical chemist Berthelot have measured the cohesion of liquids.
- The negative effect of cavitation on the performances of a ship propeller was firstly noted by Parsons (1893) who built the first experimental loop - the first hydrodynamic tunnel - for its study.
- The cavitation number was introduced by Thomas and Leroux around the years 1923-1925.

Supercavitation

When a cavity length is much greater than the body dimensions, this flow regime is described as SUPERCAVITATION.

- Supercavities have many characteristics of classical free streamline flows. The cavity interior is essentially at constant pressure, and the cavity walls are essentially free-stream surfaces of constant velocity.
- Cavity pressures approach vapour pressure.

More On Supercavitation

- Supercavitation occurs at very low pressure where a very long vapour cavity exists and in many cases the cavity wall appears glassy and stable except near the end of the cavity
- Non-cavitating flows occur at sufficiently high-pressures where there is no evidence of bubbles.
- Between these flow regimes is limited cavitation and developed cavitation.
- Limited cavitation occurs at an intermediate value of the cavitation number where amount of a given type of cavitation is minimized. Limited cavitation can be vaporous or gaseous.

Features of Supercavitating Flows

1. Supercavitation naturally occurs when the speed of a subsurface craft increases at fixed pressure P_0.

   At considerably low speeds (V>3 m/s), supercavities form when an object crosses the free water surface. In this case cavities are filled by athmospheric air and refer to artificial cavities formed at low speeds.

Features of Supercavitating Flows

2. According to the hydrodynamic scheme of supercavitation flow, the object is placed partially or fully inside a supercavity formed by the nose part (cavitator)

3. In the case of a jet cavitator system the cavity seperates from the craft hull and body has no points of contact with cavity.

Features of Supercavitating Flow

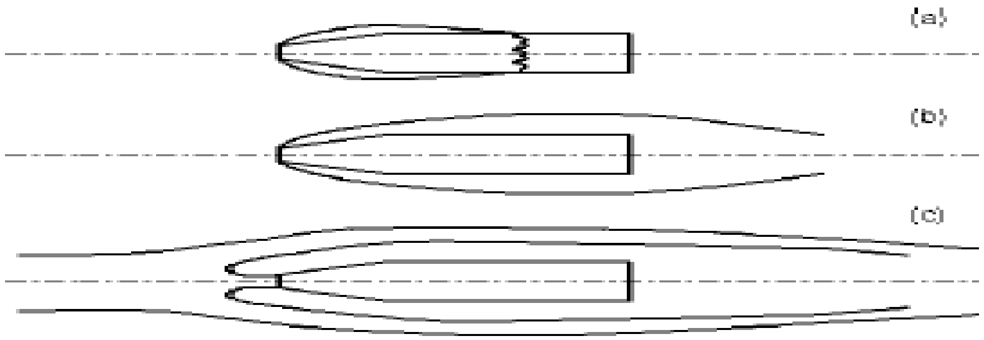


Fig. 1

Supercavitation Flow Problems

- In experimental investigation we realize a proccesses of physical modeling the supercavitation flows which includes three seperate but associate problems:

1. Modelling the supercavity shape and dimensions.
2. Modelling the main SC (Supercavity) process as gas supply, gas leakage, SC creation, SC control, SC disturbanse.
3. Modelling the supercavitating body motion.

Cavitation Flow Regimes

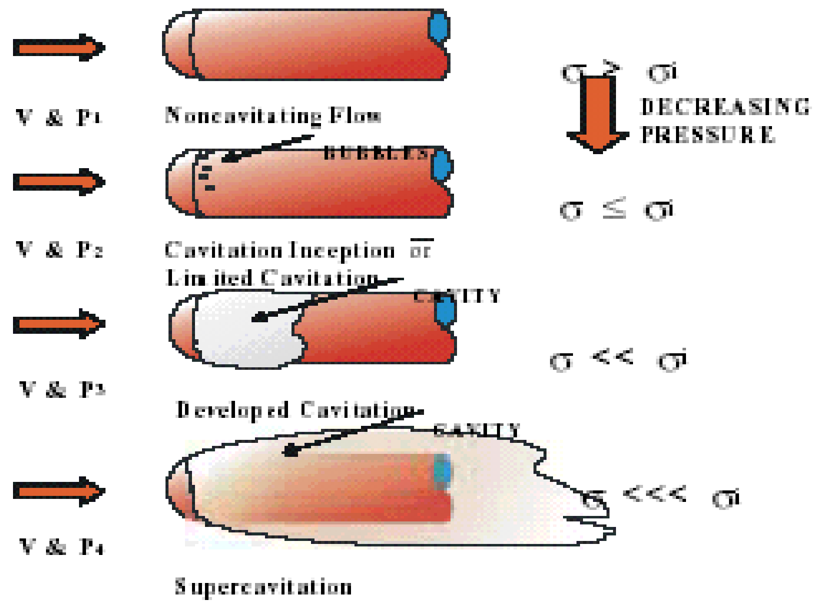


Figure 1: Schematic of cavitation flow regimes

Supercavitation Modelling by the σ Number

- The cavitation number σ is main scaling
  criterion of the supercavitation flows.
- The value of $\sigma<0.1$ corresponds to the
  supercavitation regime.
- Such values of the cavitation number are reached at velocities $V_\infty>50$ m/s.

Modelling of Supercavitating Flow

$$\sigma = \frac{2(p_\infty - p_c)}{\rho V_\infty^2}, \qquad Fr = \frac{V_\infty}{\sqrt{gL}}, \qquad \mathrm{Re} = \frac{V_\infty L}{\nu}, \qquad We = \frac{\rho V_\infty^2 L}{\zeta}. \qquad (2)$$

$$D\left(\frac{x}{D_n}\right) = D_n f_1(\sigma, Fr, \mathrm{Re}, We), \qquad F = \frac{\rho V_\infty}{2} D_n^2 f_2(\sigma, Fr, \mathrm{Re}, We), \qquad (3)$$

Modelling of Supercavitating Flow

- It is established experimentally; that the water viscosity influence is partially absent at such velocities in the case of the disk cavitator and free cavity closure.
- Influence of gravity and surface tension forces are also negligible when;

  $Fr>20\text{-}30$, $w_e>1000$

Supercavitation Modelling by the Fr Number

- It follows from the theory of similarity of hydrodynamic flows that the shape and dimensions of natural and artificial (ventilated) cavities must be equal at the same value of **σ.**
- However, this is not observed in reality.

Modelling of Supercavitaiton Flow

- The main cause is that the moderate values of the Froude number Fr<20 correspond to the flows with artificial cavitation when motion velocity V=10-50 m/s.
- It means that the gravity importance for artificial cavity is essentially greater at equality of the cavitation numbers.

Cavitator Hydrodynamics

- For supercavitaitng flow the cavitator is located at the forward most location on the body, and the cavity down-stream of the cavitator covers the body.
- The shape of the cavity is defined by the cavitation number based on cavity pressure.
- The simplest form of cavitator is a disk where the drag coefficient defined as;

$$\boxed{C_d = 0.82(1+\sigma)}$$

σ: Cavitation Number

Cavity Piercing Hydrofoil/Control Surface Testing

Cavity piercing supercavitating hydrofoil/ control surfaces have been tested in ARL Penstate 12 inch diameter water tunnel.

Figure 28: Photograph of model for testing cavitators

Figure 29: Photograph of cavitator mounted on force cell balance

Figure 30: Photograph of cavity formed by a conical nosed cavitator- continuous lighting

Figure 31: Photograph of cavity formed by a conical nosed cavitator- stroboscopic lighting

Figure 32: Photograph of cavity formed by a disk at angle of attack

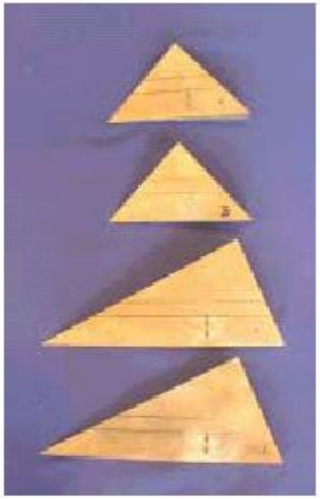


Figure 33: Cavity piercing hydrofoils having wedge shaped cross sections

Figure 34: Cavity piercing hydrofoil showing force balance and tunnel mounting fixture

Figure 35: Photograph of pressure side of cavity piercing hydrofoil

Figure 36: Photograph of suction surface of cavity piercing hydrofoil that shows cavity disturbances due to imperfections along leading edge.

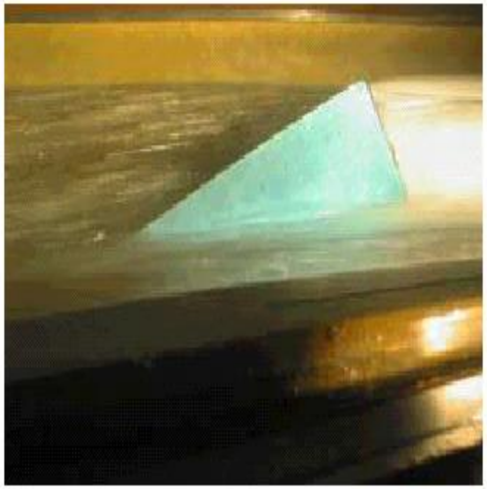


Figure 37: Photograph of cavity piercing hydrofoil at low angle of attack, with base cavitation

Figure 38: Photograph of cavity from higher aspect ratio cavity piercing hydrofoil

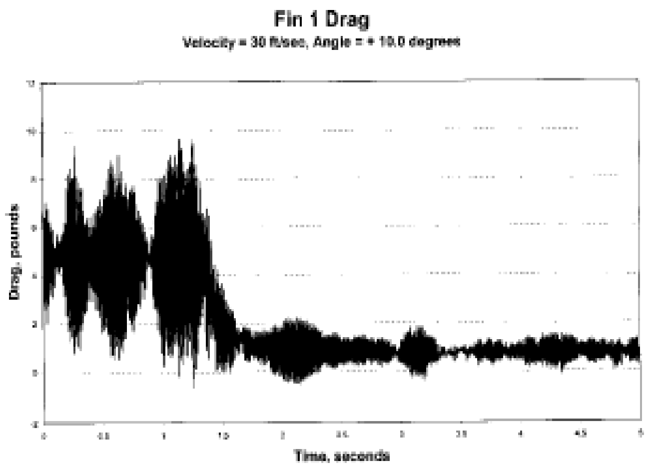


Figure 44: Drag force as a function of time, supercavitation

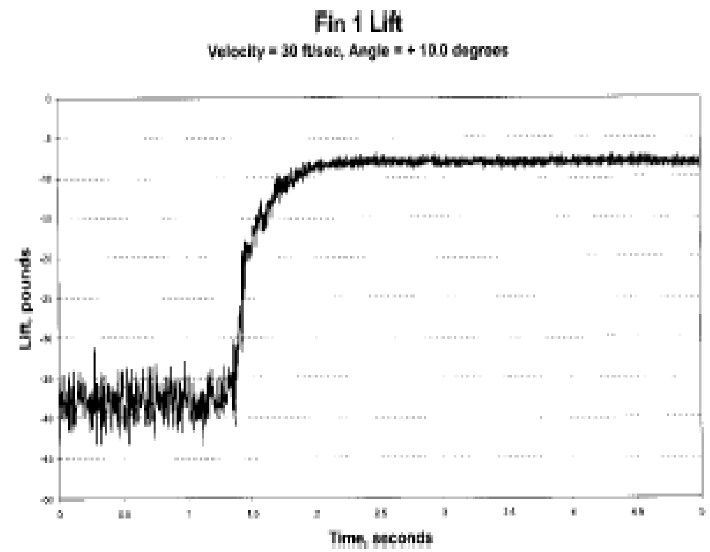


Figure 45: Lift force as a function of time, supercavitation

Design of Supercavitating Propeller

- An optimization method (CAVOPT-3D), similar to that supercavitating hydrofoil sections, has been developed.

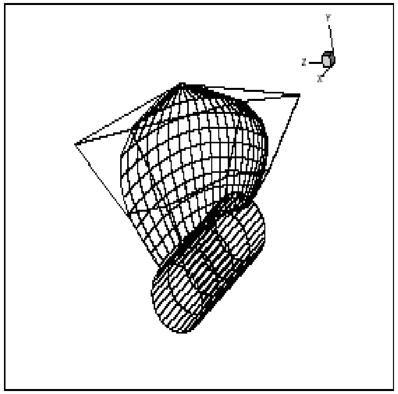
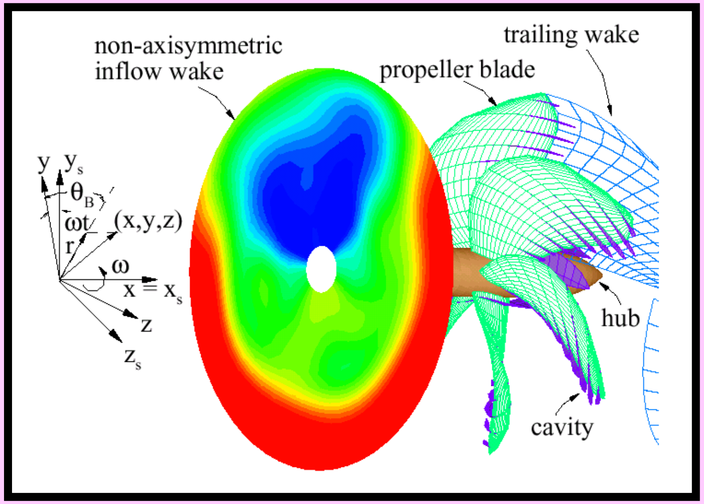


Figure 47: B-spline polygon and the paneled blade geometry in CAVOPT-3D/MPUF-3A.

Design of Supercavitating Propeller

- The coefficients of the objective function are determined in terms of second order Taylor expansions from the result of MPUF-3A, a vortex and source lattice method for cavitating propellers in unsteady flow.
- This method determines both the optimum cavitating propeller loading and the corresponding blade geometry at the same time.

- The required input design variables required by CAVOPT-3D to set up the design model are given as;
    - advance coefficient (J_s)
    - cavitation number (σ_n)
    - froude number (Fn)
    - number of blades (z)
    - hub radius (r_H)
    - required thrust coefficient (K_{T0})
    -Inflow wake distribution



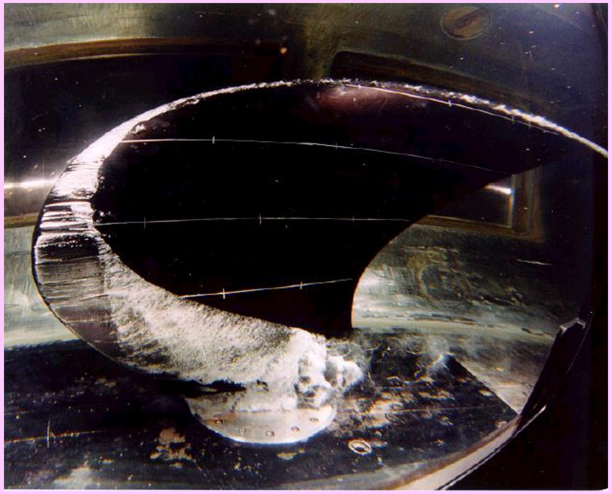
Application

- The 3-D method has been applied more recently for the design of a supercavitating propeller.
- The original thickness distribution, has been used as input in CAVOPT-3D. We have forced leading-edge cavity detachment in MPUF-3A.
- The same design conditions as those of the SRI propeller are used for CAVOPT-3D.

New Design

- The new design has a substantially larger efficiency 74.7 % ie. increase in efficiency of over 7 %.
- The new design has a wider blade area and a lower pitch (for the same thrust).
- The predicted cavities for the new design are thinner at the leading edge as well as at the trailing edge, thus resulting into a smaller cavity drag.
- The new design may lead to midchord cavitation and this will increase its frictional drag, and degrade some what the expected higher efficiency.

- The principle of functioning of the cavitation tunnel, which represents a vertically mounted hermetically sealed variable diameter tube, is extremely simple.
- This experimental installation enables to conduct the force measurement and visual observations of models of the cavitating or supercavitating propeller for given magnitudes of advance coefficient and axial cavitation number , which are taken equal to those of the full size propellers for a regime under consideration.



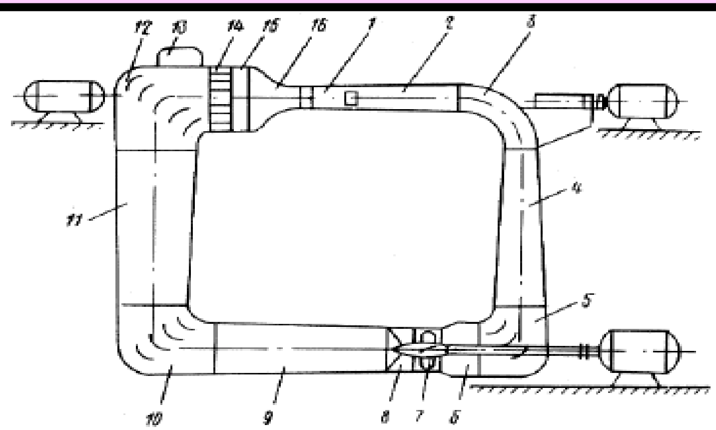
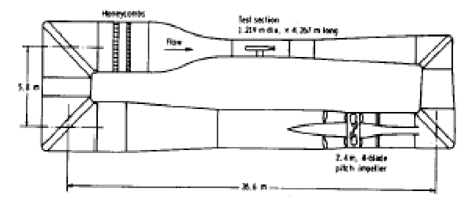


Fig.1. Cavitation tunnel
1.Working section
7.Impeller
8.Aline device
13.Variable pressure shaft
14.Honeycomb rectifier

CAVITATION TUNNEL (GARFIELD THOMAS) 1949



Description of Facility: Closed Circuit, Closed Jet

Type of Drive System:4-Blade Adjustable Pitch Impeller

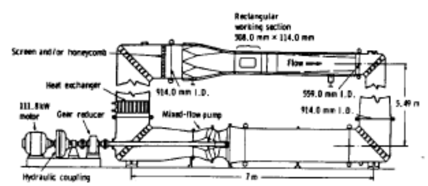
Total Motor Power:2000 HP Variable Speed (1491 kW)

Working Section Max. Velocity: 18.29 m/s

Max. & Min. Abs. Pressures:413.7 to 20.7 kPa

Cavitation number Range:>0.1 dependent on velocity and/or J-range

CAVITATION TUNNEL 1951



Description of Facility: Closed Circuit, Closed Jet

Test Sections:(1) Circular: 304.8 mm dia x 762.0 mm long

(2) Rectangular: 508.0 mm x 114.3 mm x 762.0 mm long

Type of Drive: Mixed Flow Peerless Pump

Total Motor Power: 150 hp (11.8 kW)

Working Section Max. Velocity:24.38 m/s

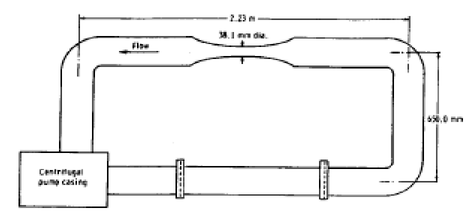
Max. & Min. Abs. Pressures: 413.7 to 20.7 kPa

Cavitation Number Range:>0.1 dependent on velocity

Instrumentation:Lasers, pressure sensors, hydrophones

Model Size Range:50.8 mm max. dia.

ULTRA-HIGH SPEED CAVITATION TUNNEL 1960



Description of Facility:Closed Circuit, Closed Jet

Type of Drive System:Centrifugal Variable Speed Drive

Total Motor Power: 75 hp (55.9 kW)

Working Section Max. Velocity: 83.8 m/s

Max. & Min. Abs. Pressures:8274.0 to 41.4 kPa

Cavitation Number Range:>0.01 dependent on velocity and velocity

Instrumentation:Pressure and temperature sensors, lasers

Temperature Range:16°C to 176°C

Model Size Range:12.7 mm max. dia.

Test Medium:Water, Freon 113, Alcohol

- In the case of supercavitation, which depend to

- a lesser degree on the vertical distribution

  of the hydrostatic pressure

- Viscosity
- Turbulence
- Air content and other factors not taken into account.

- It should be noted that some of the forms of cavitation are either poorly modeled in cavitation tunnel, or require application of the special procedures for recalculation of the model results to those in full scale.
- Examples include cavitation of the tip and axial vortices. Large difficulties occur when modeling of erosion, noise and vibration of the cavitaitng propeller.

- Nonetheless, the most important factors (criteria) during in testing of the supercavitating propellers in the cavitation tunnel are the advance coefficient.

  $J=V/(nD)$

  and the axial cavitation number

  $v= (P_0-P_v)/ (0.5\rho V^2)$

  P_0- hydrostatic pressure at the level of the SCP axis.

  P_v – pressure of saturated vapour of the fluid at the temperature of the testing.

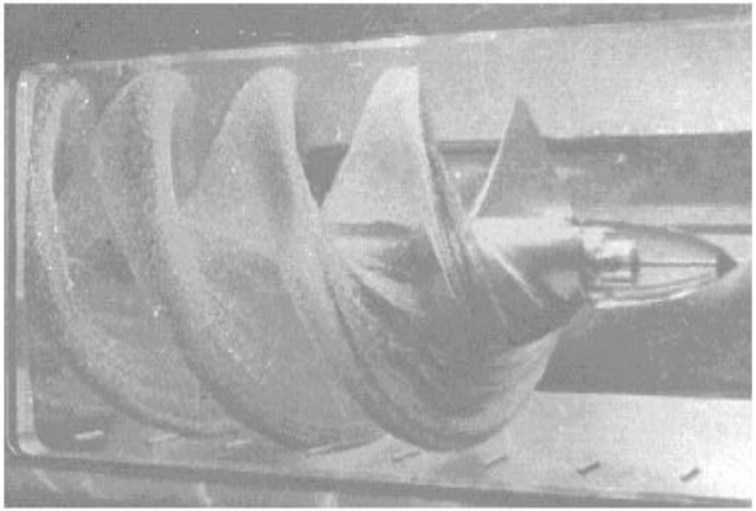


Fig.3.Propeller operating on supercavitating regime [16]

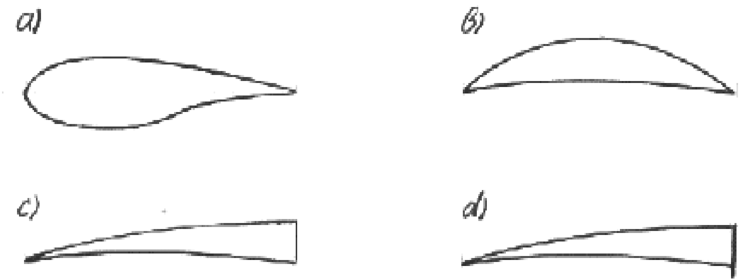


Fig.4.Blade section types
a)conventional
b)segment
c)wedge-shaped (supercavitating)
d)wedge-shaped with a spoiler (supercavitating with a spoiler)

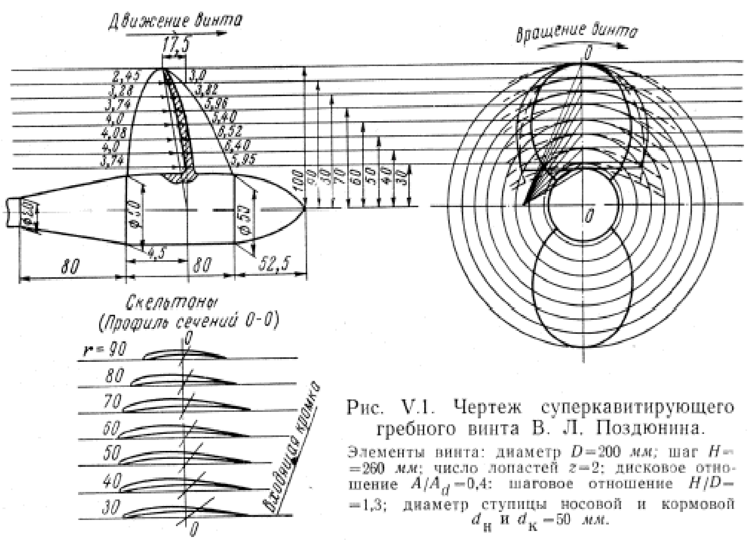


Fig.2.Posdunine's supercavitating propeller drawing [55]
(D=0.2m., p=0.26m., A_E/A_0=0.4)

- First of all, it turned out to be of preference for supercavitating propellers to employ a special wedge type profiling, drasticly different from the one additionally used for the non-cavitating screw propellers.

- An important conclusion can be made on the basis of the foregoing material.
- When designing a supercavitating propeller for a hydrofoil ship the project optimization at the regime of maximal speed should be performed in such a way that a sufficient thrust be provided at the drag hump regime with account of the power plant available on board.

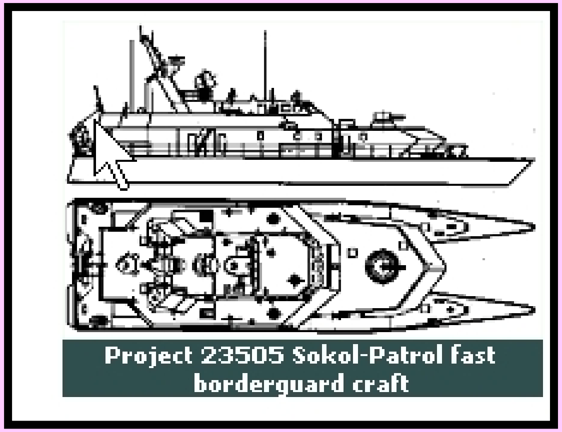
- In short, the high efficiency at the maximal speed regime is not the only requirement when designing a supercavitating or a highly cavitating propeller for a hydrofoil ship.

- The analysis of hydrofoil revealed, in particular, an important peculiarity of such propellers, namely, for a given low cavitation number and at a given magnitude of the advance coefficient the increase of pitch for the supercavitating propeller as opposed to a non-cavitating one, does not lead to a significant increase of the thrust coefficient.

The Story of Supercavitating Screw Propeller

- The story of the application of the supercavitating screw propellers proper, which started successfully in 1962 from the hydrofoilship “Dension”, finishes over by the end of the 80s, because the experience of operation of this screw propellers on the world largest serial hydrofoil ships of the “Sokol” type showed insufficient reliability of the shaft sealing on the naceless and ensuring necessity in frequent repair.

- **Project 23505 Sokol-Patrol Fast Borderguard Craft**
  - Displacement, t: standard 123 full 137
  - Dimensions, m: overall length 36.5
  - maximum beam 11.0
  - midboard height 3.8
  - design draught 1.6
  - http://www.milparade.com/1999/36/05_03.shtml

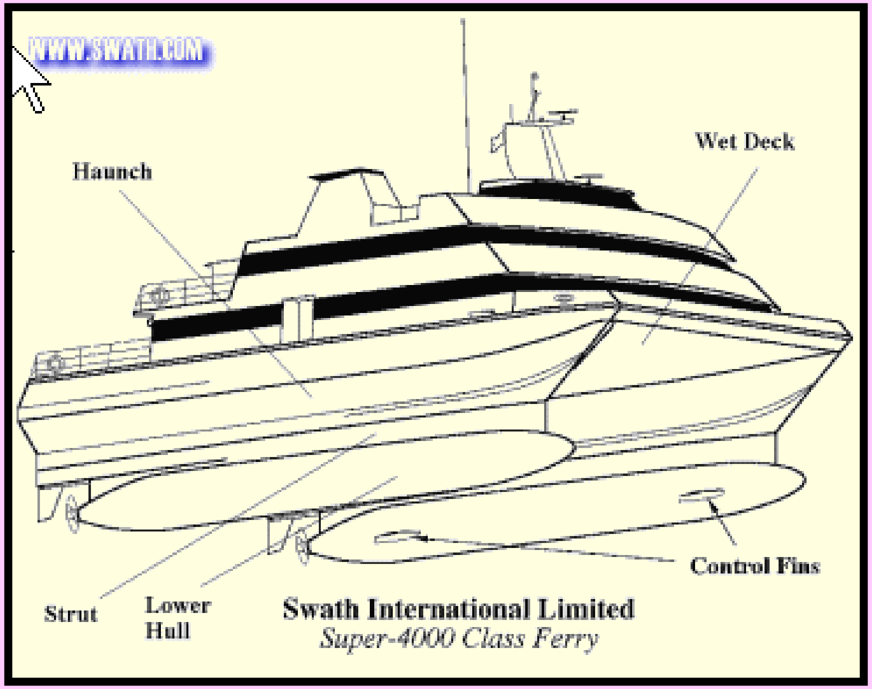


- The problem of reliability become so
  acute that it was decided to equip the
  next projects of the Russian open
  ocean hydrofoil ships not with
  supercavitating propellers but with
  wateriest similarly to the U.S. hydrofoil
  ships “Tucumcari” and “Pepas”.

Tucumcari

http://www.navsource.org/archives/12/1002.htm

- However, these projects have not been realized. Further on, unfortunately, the interest toward the hydrofoil ships in the world dropped quite abruptly in connection with appearance of more prospective types of high-speed ships, such as catamarans, SES (Surface Effect Ships) and SWATH (Small water-plane area twin hull), for which implementation of the supercavitating propellers proper is not preferable.



Swath concept

Typical application