"Mircea cel Batran" Naval Academy Scientific Bulletin, Volume XVII – 2014 – Issue 2
Published by "Mircea cel Batran" Naval Academy Press, Constanta, Romania // The journal is indexed in: PROQUEST SciTech Journals, PROQUEST Engineering Journals, PROQUEST Illustrata: Technology, PROQUEST Technology Journals, PROQUEST Military Collection PROQUEST Advanced Technologies & Aerospace

THEORETICAL AND EXPERIMENTAL REASEARCHES UPON THE CAVITATION PHENOMENON OF THE AXIAL PUMPS

Beazit ALI [1]
Levent ALI [2]
[1] Professor, PhD. Eng., "Mircea cel Batran" Naval Academy, Constanta
[2] Eng, PhD attendee Military Technical Academy, Bucharest

***Abstract**: This working research presents an original approach of the cavitation processes taking into consideration similar phenomena which are producing in nature. This new vision about cavitation phenomenon offers us other ways to study it, among these the similarity theory .In the working research are presented also the methods which can make possible the removing or the slowing down of cavitation process which starts during the navy propeller and carrying wings function.*

By analysis the theoretic and experimental phenomenon it establish the implicit function which describes this phenomenon. By application the Π theorem for this implicit function it finds the criterion equation of phenomenon.

Depending on operating condition various cavitation patterns can be observed on a body surface as travelling bubbles, attached sheet cavitation, shear cavitation or vortex cavitation. Leading edge attached partial cavitation is commonly encountered on rotor blades or on hydrofoil. It corresponds to the case for which a vapor cavity is attached in the vecinity of the leading edge and extends over a fraction of the foil surface. It generally takes places at incidence angles for which a leading edge pressure peak occurs and reduced below the liquid vapor pressure. At the early phases of development, leading edge partial cavitation is steady.

***Keywords:** The bubble's implosion, incompressible liquid, the bubble surface, the Π theorem.*

1. INTRODUCTION

There are situations when in different zones of a liquid's current the static pressure of the liquid falls below the evaporation pressure value, at the temperature of the respective environment. In these zones the process of water evaporation begins; the mass of current produced by liquid becomes discontinuous; at this stage bags of water and gas, which were previously present in water (dissolved in it and absorbed by it at high pressures) can appear. If these gas and liquid bags are carried by the liquid current towards other zones of the current, where the static pressure is bigger than the pressure at which the vapors were created, then a sudden condensation of water vapors takes place, thus generating vacuum pockets (in the space initially occupied by vapors) which absorb the surrounding liquid at extraordinary high speeds. As a result, the liquid hits the metallic surfaces, which delimited the space of the vapor bags with great force, thus provoking the detachment of metallic micro-particles which belonged to the rigid walls that delimited the mass of the liquid current. Since the absorption speed of the liquid towards the liquid bags can become extremely high there can be a possibility for the static pressure to fall again below the evaporation pressure value at the respective temperature, thus generating a new evaporation of the liquid that can be followed by a new condensation of vapors and by absorption of the surrounding liquid towards the space delimited by the respective metallic surfaces, with a new micro-particle detachment.

The repeated vaporization and condensation process, followed by pressure shocks with metallic micro-particle detachment is called cavitation.

2.THEORETICAL CONSIDERATIONS ON CAVITATION

As it is known, the problems related to cavitation haven't been resolved theoretically, although much research and experiments have been, and is still being made. It appears curious that this important issue hasn't, at least, been inferred appropriately, according to the inner structure of the phenomenon. Researchers in this domain seem not to have understood that the process of cavitation is similar, structurally, with the phenomenon of vapor condensation, present in the earth's atmosphere, that appear during rain seasons. It is logical then, to understand that the electric discharges during rain seasons can appear at a smaller scale, even in the process of cavitation. The occuring of the electric sparks in the process of current cavitation should not appear surprising to anyone, nor should the bio-electromagnetism of the human body and other beings; they are subordinated to the same structural laws of universal electromagnetism. Probably, the phenomenon of electric spark occurance can be more easily understood when it is compared with the pneumatic transportation of flour, used by whet mills. It is known that disastrous fires happened, many times, during the pneumatic transportation of flour; they were caused by electrostatic discharges within the pipes used for pneumatic transport. The same electrostatic discharges may appear when gasoline is transported in plastic containers.

We are hopeful that electromagnetism and electrostatic discharges, of which we have talked, will soon be known, reproduced and used for the benefit of humanity. Only then cavitation and rain phenomena will be mastered, and corresponding possibilities of generation and stopping will be created for them.

The electrostatic charge of water vapors that creates the clouds in the terrestrial atmosphere or in spaces where cavitation is generated – having as a consequence electric discharges (lightnings or electric sparks) – is a problem for the science of the future to be solved, with all the benefits that may come out of this.

The occurrence of cavitation is followed by an abnormal sound, and by the vibrations that lead to the decrease of efficiency, volume and charge of hydraulic installations.

Avoidance of cavitation requires that the static pressure of the flowing water should not become equal or smaller than its evaporation pressure at the respective temperature.

The increase of ship speed has a great influence on the propellers functioning, because with the increase of the flow speed through the propellers' blades, the static pressure of the liquid decreases, sometimes below the value of the evaporation pressure, thus leading to the occurrence of cavitation.

The presence of certain gas or vapors bags disrupts the homogeneity of the current flow, this happening when the sector in which cavitation takes place is sufficiently big; in this case the hydrodynamic characteristics of the support profile.

At present there is not any theoretical formulation to state corresponding relations between the size of the cavitation region and the effect on the hydrodynamic profile characteristics.

The word "cavitation" comes from the Latin "cavitas", which means "empty" (inside). In reality the bags of fluid that generate cavitation are filled with a mixture of water vapors and gas.

Supposing the profile's section is moves at a speed $v_{0,}$ in an ideal liquid, with density ρ.

If we note with p_A the pressure in a certain point on the surface of the profile, with v_A the local speed in this point, and with p_0 the static pressure in the undisrupted liquid:

According to the BERNOULLI equation, we have:

$$p_A = p_0 - \frac{\rho}{2}\left(v_A^2 - v_0^2\right) \qquad (1)$$

From the above relation we see that the local pressure on the surface of the profile decreases with the increase of the dynamic pressures $\frac{\rho}{2}\left(v_A^2 - v_0^2\right)$, and when this difference becomes equal with the static pressure of the undisrupted environment of the local pressure becomes invalid. The more the $\frac{\rho}{2}\left(v_A^2 - v_0^2\right)$ increases, the smaller the pressure p_A becomes; this leads to the generation of the cavitation phenomenon, with liquid detachment off the metallic surface that delimits its volume.

The occurrence of cavitation on the rotor's blades is followed by a release of air bubbles that spread into the water. If the revolution of the rotor is increased, at a certain moment, there can appear vapors and gas on the surface of the propeller, in zones with minimum pressure. These bubbles are moved by the water current. The release of vapors and gases, with the condensation of vapors is responsible for the rotor's sound. As the rotor's revolution movement increases, there may be a possibility for the rotor to be surrounded by a pocket of vapors; the wings lose the vapor bags and as well as the sustaining force of the raised water current. Cavitation re-appears and there appears another phenomenon- ship's galloping.

We can infer from the above mentioned that cavitation can appear when the static pressure of the liquid becomes equal or smaller than the evaporation pressure at the respective temperature of the environment. The following relations can be written:

$$p = p_0 - c_{p_{\max}} \cdot p_d \le p_v \qquad (2)$$

where:

p_0 – the static pressure of the undisrupted liquid

p - pressure in a point on the surface of the liquid

p_v - the vaporization pressure of at the respective temperature of the environment

$$p_d = \frac{\rho v_0^2}{2} \text{ - dynamic pressure}$$

$$c_{p_{\max}} = \frac{p_0 - p_v}{\frac{\rho v_0^2}{2}} = c_p = K$$

K - pressure coefficient or cavitation number

As we have already mentioned when the entire bearing wing is surrounded by a bag of water vapors, its sustaining force is 800 times reduced because ρ_{aer} is aproximately 800 times smaller than ρ_{apa}.

The values of rotor's pushing and efficiency depend at a great extent on number of cavitation K, which at its turn depends on the speed march.

The values of cavitation number span within the interval $0{,}2 \le K \le 2$.The small value refer to fast rotors, and the big ones to the slow rotors.

Up to the present there is no theory referring to the corresponding relations between the size of the cavitation region and the effect produced on the hydrodynamic characteristics of the propeller.

Experiments on mock-ups are made in cavitation tunnels in which variation of speeds and pressures can be controlled, which allows the making of an analysis of the dependence between the evolution of cavitation and that of the propeller's pushing capacity, and the rotor's momentum, as well as of moment in which cavitation becomes dangerous for the thruster's performances. By systematic experiments specialists drew the conclusion that the main criteria according to which the propellers should be modeled when they suffer the phenomenon of cavitation is the equality of cavitation numbers $K_m = K_n$, on the mock-up.

$$\frac{p_{0m} - p_{vm}}{0{,}5\rho_m v_{0m}^2} = \frac{p_{0n} - p_{vn}}{0{,}5\rho v_{0n}^2} \qquad (3)$$

In which with m were noted the measurements related to the model, and with n those referring to the prototype.

In the evolution of the process of cavitation there are other similitude criteria, which assure the similitude between the phenomenon on the model, and the one on the prototype, namely: REYNOLDS, NEWTON and WEBER.

The FROUDE criteria can be left apart under appropriate immersing conditions, and for the REYNOLDS number, a value, small enough so that all the sectors of the blades be under the critical limits, should be provided. As to what the WEBER criteria is concerned (which modifies the forces of superficial tension) practically it is impossible to realize an equality both on the model and on the prototype of this criteria; attention should be paid on the air content of the water in the basin, on which the evolution of the process of cavitation depends. The fact that the beginning of cavitation depends on the angle of attack α, should not be neglected; the bigger the angle of attack, the sooner the process of cavitation begins.

3. USING THE SIMILITUDE THEORY ON TWO SCALES IN THE EXPERIMENTAL STUDY OF THE CAVITATION PHENOMENON

There are situations when the possibilities of accomplishment of the pattern impose exceptions from the complete geometrical similitude, obtaining this way the distorted patterns which have horizontal lengths and vertical lengths reduced to different scales.

Generally, the distorted patterns are imposed when the possibilities of practical accomplishment make impossible the exact conformation of the geometrical similitude between the pattern and the prototype, or when evolution of the phenomenon on the pattern made at a single scale would lead to a laminar movement instead of turbulent one which would make all the experiments difficult.

A random physical phenomenon can be expressed in the most general way through a function of several physical proportions and the establishment of the connection between them is made (when the number of the physical proportions $n \ge 5$) through theorem Π.

Any homogeneous function of several physical proportions which determine a physical phenomenon can always be reduced to a relation between dimensionless complex proportions of the following formula:

$$\Phi(\Pi_1, \Pi_2, \ldots\ldots, \Pi_{n-k}) = 0 \qquad (4)$$

In the theory of similitude this function is called criteria equation and its establishment represents the first phase of the pattern study of a phenomenon.

As it is known the cavitation problems have not yet been solved, theoretically or practically, worldwide, although researches are made to this respect.

If we want to study this phenomenon through the similitude theory, we should previously set the physical proportions that intervene within the evolution of the cavitation phenomenon on the rotor of the axial pumps.

The criteria equation for the cavitation phenomenon produced at the wheels of the axial pumps

After theoretical and experimental researches made until now, it has been established that the cavitation phenomenon at the rotor of the axial pumps has the following implicit function:

f (ρ, *n, D,T,* Δp ,*h,* $d_{\max}$,*g,* η ,*v, m, z*)=0 (5)

where:

ρ - water density

n - wheel speed

D - wheel diameter

T - wheel pusher

$\Delta p = p - p_v$ -pressure distribution on the blade

p_v – water vaporization pressure at certain temperature;

h - immersion of the wheel axis on the water surface

$d_{\max}$ - maximum thickness of the wheel blade;

g - gravitational velocity g = 9,81 m/s^2;

η - water kinetic viscosity ;

v - current velocity through the rotor disk;

m - air volume dissolved in water;

z - number of the wheel blades.

The physical proportions of this implicit function actually represent the physical proportions which this phenomenon depends on.

In order to apply theorem Π to the implicit function, we first write the dimensional matrix of the variables (number of rotor blades z is the same both as pattern and prototype).

	ρ	n	D	T	Δp	h	$d_{\max}$	g	η	v	m
m	−3	0	1	1	−1	1	1	1	−1	1	0
Kg	1	0	0	1	1	0	0	0	1	0	1
s	0	−1	0	−2	−2	0	0	−2	−1	−1	0

(6)

$$\left\{\begin{Vmatrix} -3 & 0 & 1 & 1 & -1 & 1 & 1 & 1 & -1 & 1 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & -1 & 0 & -2 & -2 & 0 & 0 & -2 & -1 & -1 & 0 \end{Vmatrix}\right.$$

out of which we obtain the equations system:

$$\begin{cases} -3x_1 + x_3 + x_4 - x_5 + x_6 + x_7 + x_8 - x_9 + x_{10} = 0 \\ x_1 + x_4 + x_5 + x_9 + x_{11} = 0 \\ -x_2 - 2x_4 - 2x_5 - 2x_8 - x_9 - x_{10} = 0 \end{cases} \quad (7)$$

We sort out the main variables of the system:

$$x_1 = -x_4 - x_5 - x_9 - x_{11}$$
$$x_2 = -2x_4 - 2x_5 - 2x_8 - x_9 - x_{10} \quad (8)$$
$$x_3 = -4x_4 - 2x_5 - x_6 - x_7 - x_8 - 2x_9 - x_{10} - 3x_{11}$$

System (3) is undetermined for solving, so we apply the Cramer rule and we obtain the solution matrix as it follows:

	ρ	n	D	T	Δp	h	$d_{\max}$	g	η	v	m
Π_1	−1	−2	−4	1	0	0	0	0	0	0	0
Π_2	−1	−2	−2	0	1	0	0	0	0	0	0
Π_3	0	0	−1	0	0	1	0	0	0	0	0
Π_4	0	0	−1	0	0	0	1	0	0	0	0
Π_5	0	−2	−1	0	0	0	0	1	0	0	0
Π_6	−1	−1	−2	0	0	0	0	0	1	0	0
Π_7	0	−1	−1	0	0	0	0	0	0	1	0
Π_8	−1	0	−3	0	0	0	0	0	0	0	1

(9)

Out of the solution matrix we obtain the following similitude criteria:

$$\Pi_1 = \frac{T}{\rho n^2 D^4}; \Pi_2 = \frac{p - p_v}{\rho n^2 D^2}; \Pi_3 = \frac{h}{D}; \Pi_4 = \frac{d_{\max}}{D};$$
$$\Pi_5 = \frac{g}{n^2 D}; \Pi_6 = \frac{\eta}{\rho n D^2}; \Pi_7 = \frac{v}{nD}; \Pi_8 = \frac{m}{\rho D^3} \quad (10)$$

The criteria equation in which we shall include the number of blades z, shall be as it follows:

$$\varphi\left(\frac{T}{\rho n^2 D^2}, \frac{p - p_v}{\rho n^2 D^2}, \frac{h}{D}, \frac{d_{\max}}{D}, \frac{g}{n^2 d}, \frac{\eta}{\rho n D^2}, \frac{v}{nD}, \frac{m}{\rho D^3}, z\right) = 0 \quad (11)$$

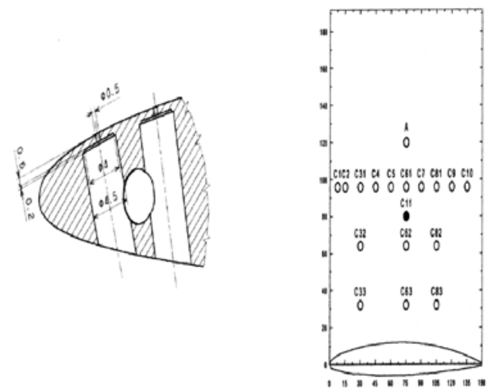
If we respect the geometrical similitude after a single scale, it is possible that the thickness of the wheel blade and the immersion of its axis to reduce a lot, therefore it is possible that the pattern not to be able to be used for determinations, the results including too many errors.

Because of this, it is more advantageous and safe to create the distorted blade patter (at two scales), which allows more accurate results.

It can be determined the pattern law in the case of similitude at two scales, by randomly choosing the scale of the parallel lengths with the blade diameter and the scale of the parallel lengths with the thickness of the blade.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

An investigation of leading edge partial cavitation was performed in Romania (ICEPRONAV – Galați) including the conditions of cavitation inception, the cavitation patterns together with cavity length measurements. The investigation was enhanced by instantaneous wall-pressure measurements using an instrumented blade of rotor equipped with seventeen wall-pressure transducers mounted into small cavities, (fig 1).



a) b)

Fig. 1, a) Transducer cavity, b) Location of the pressure transducers, filled symbol is on the pressure side, A referees to an accelerometer, unit in millimeter.

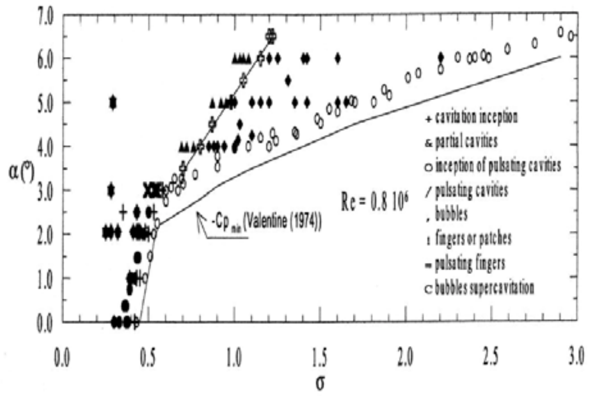


Fig. 2

All the experiments fitted with a 1m long and 0,192 m wide square cross test section. In this device, velocities of up to15 m/s and pressures between 30 mbar and 3 bar can archieved. The designed blade for this project is a 0,191 mm span two - dimensional cambered foil of the NACA 66 . Several experimental results have been obtained. Figure 2 shows the inception conditions and the various patterns detected on the suction side of the foil versus the cavitation number and the angle of incidence. The inception conditions are also compared to the theoretical values of the opposite of the minimum pressure coefficient on the suction side. Partial cavities of intermediate length (l*lower than about 0,5) have a relatively stable behavior with weak variation of the cavity closure while shedding U-shaped vapor structures in the wake. In that situation the cavity length was measurable (see fig. 3). As shown on fig. 4, the liquid-vapor interface has a glossy aspect over a short distance from the leading edge indicative of a laminar boundary layer developing on the interface. The extent of the laminar flow was found to be dependent on the velocity (Figures 4.b and 4.c for the same cavitation number but two velocities). Further away the interface becomes wavy and unstable over a large fraction of the cavity length. When the cavity becomes large, typicalli l/c larger than about 0,5, it exhibits a pulsating behavior while shedding larger vapor-filled structures. The transition is relatively well represented by the straight line shown on fig 1.

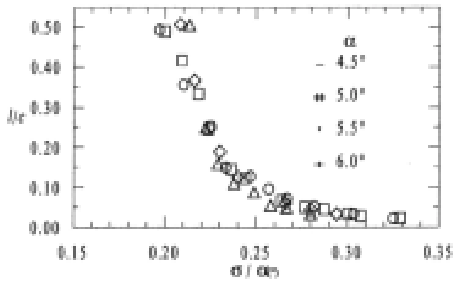


Fig. 3 Cavity length as a function of $\frac{\sigma}{\alpha}$, Re = $8 \cdot 10^6$

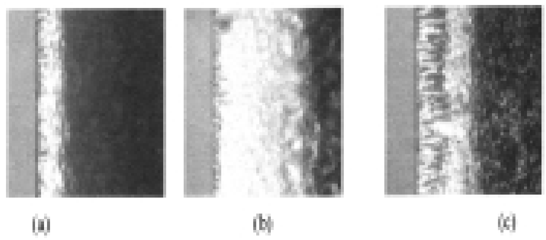


Fig. 4. Photographs of leading edge partial sheet cavitation, NACA 66-12% - 100mm foil, flow is from the left, α = 6, a) Re = $8 \cdot 10^6$, $\sigma = 1{,}98$, l/c= 0,045

b) Re = $8 \cdot 10^6$,σ = 1,31, l/c=0,325. c) Re=0,4$\cdot 10^6$, σ = 1,30, l/c=0,205.

5. CONCLUSIONS

If the positive angle of attack α is big the process of cavitation appears on the back of teh profile, beginning with the board of attack.

In case both the positive and negative angles of attack are smaller, cavitation appears on the exterior back of the profile, approximately on its middle part. In this case, at great speeds of the current of translation and when the thickness of the profile is big, cavitation can extend on the interior back, and in Duch a case the whole profile will be surrounded by a bag o fair and gas. In the case of big, negative angles of attack, cavitation can appear on the interior back of the profile beginning with the borrad of attack.

In order to stop the phenomenonof cavitation of teh propeller, it is necessary to fit up, at a relatively small distance, a wing, named cavitation stopping wing. On the interior back of this wing, while the slip is underway, the pressure increases and thus the phenomenon of cavitation is stopped. Experiments on propellers mock-ups, in cavitation models allow the set up of of all the factors that produce cavitation. These are: the overloading of propellers, the big turning speed of the propeller, th small stern draft, the ship's high speed, the low efficiency of the thruster, great sliding and small pitch, big number of propelles, poor polishing of teh propellers' blades, the big thickness of the blades, blades with inappropriate hidrodynamic profiles. As it was seen, all the factors that appear in a propeller's designing have influences on cavitation; however one can not set the pririties of teh phenomena which generate cavitation.

Used in distributions, the equations form in the fluid mechanics and the filtration property of the Dirac distribution, several integral formulas regarding the cavitational implosion are obtained.

The mathematic pattern, which only describes the fluid movement, can only indicate something about the hydrodynamic effects of the cavitational implosion, the thermal and electrochemical effects, experimentally presented, can be analogously analyzed.

After knowing the non dimensional complex numbers which form the criteria equation, before making the pattern of the studied phenomenon we shall establish the connections between the scales of the physical proportions which determine these complex numbers, that is we shall establish the pattern law. Being familiar to the distorted pattern law, we can transfer the proportions results obtained on the pattern, on the prototype.

We notice that not all the similitude criteria have the same importance in the evolution of the cavitation process of the axial pumps blades. The most important criterion, decisive in the cavitation process, is the one in which the vaporization pressure intervenes p_v.

The cavity lenght does not change significantly, the liquid – vapor interface is smooth and has a glossy aspect along a short distance from the leading edge. At the end of the cavity it breaks partially into small bubbles. As the cavity expands, the liquid – vapor interface become distorted, wavy and unstable yielding to breakup and unsteadiness. At this stage significant variations of the location of the cavity closure point are observed while shedding vapor structures called „cloud" cavitatin. This process induces high - level pressure pulses and is known to be one of the most destructive forms of cavitation.

6. REFERENCES

[1] I. Anton, *Cavitation*, Bucharest, 1984
[2] G. Baran, *Cavitation*, Course of the Polytechnic Institute Bucharest, 1994
[3] L. Burlacu, *Analytical Mathematics*, Bucharest, 1983
[4] C. Iacob, *Classical and modern mathematics*, vol. IV, Bucharest, 1984
[5] I. Anton, *Cavitation*, vol. I and II, Academy Publishing, Bucharest, 1980
[6] B. Ali, *Hydrodynamics of the wing span, control of cavitation and the stability of the hydrofoil ship*, Scientific Paper II, Galati, 1996
[7] Al. A. Vasilescu, *Dimensional analysis and the similitude theory*, Academy Publishing, Bucharest, 1969.
[8] V.Teodorescu, *Equations of mathematical physics*, Course of the University of Bucharest, 1982.
[9] Beazit Ali, Cornel Moroianu, *Studiul teoretic şi experimental al fenomenului de cavitaţie la pompele axiale*, Buletinul Sesiunii Ştiinţifice "Tehnonav 2002", p. 177 - 181 – Universitatea "Ovidius" Constanţa, 2002
[10] Beazit Ali, Patrichi Ilie, *Studiul teoretic şi experimental al fenomenului de cavitaţie la turbomaşini,* Analele Universităţii Maritime din Constanţa, anul IV, vol. 5, 2003, p. 77 – 84.
[11] Beazit Ali, Adriana Sporiş, Levent Ali, *Studiul teoretic al fenomenului de cavitaţie la profilele portante.,* Buletinul Sesiunii de comunicari stiintifice Navmaredu 2007 – Academia Navală „Mircea cel Bătrân", Constanţa, noiembrie 2007 , p. 19 - 24