EVALUATION OF CAVITATION PERFORMANCE OF AN AXI-SYMMETRIC BODY WITH PUMPJET PROPULSOR

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SUMMARY

A Pumpjet (PJP) was designed for an underwater body (UWB) with an axi-symmetric configuration as part of a technology development program for design and development of pumpjet. Its propulsive and cavitation performances were predicted through CFD study. The propulsor design was evaluated for its propulsion characteristics through model tests conducted in a Wind Tunnel. In the concluding part of the study, evaluation of the cavitation performance of the pumpjet was undertaken in a Cavitation Tunnel (CT).

In order to assess the cavitation free operational speeds and depths of the vehicle with respect to pumpjet, cavitation tests of the PJP were carried out in behind condition at CT to determine the cavitation inception numbers for rotor, stator and cowl. The model test results obtained were corrected for full scale Reynolds number and subsequently analyzed for cavitation inception speeds at different operating depths. This entire exercise facilitated the development of an innovative testing technique and a special test setup for finding cavitation performance of pumpjet propulsor. The technique was evaluated by comparative corroboration of inception position and depth obtained from CFD analysis. From the model tests it was also found that the cavitation inception of the rotor takes place on the tip face side at higher advance ratios and cavitation shifts towards the suction side as the shaft rotation rate increases whereas the stator and cowl are free from any cavitation.

NOMENCLATURE

D	= Propeller diameter, (m)
D_f	= Full scale propeller diameter, (m)
D_m	= Model scale propeller diameter, (m)
h	= Submergence of propeller axis, (m)
J	= Advance coefficient
P_{ts}	= Test section static (gauge) pressure, (Pa)
P_l	= Local static (gauge) pressure at pumpjet, (Pa)
P_a	= Atmospheric pressure, (Pa)
P_v	= Saturation vapor pressure of water, (Pa)
n	= Propeller revolutions per second, (RPS)
n_f	= Critical speed of full scale propeller (RPS)
n_m	= Model propeller revolutions per second, (RPS)
V	= Tunnel flow speed, (m/s)
R_n	= Propeller Reynolds number
σ_i	= Cavitation inception number
σ_m, σ_{model}	= Model propeller cavitation inception number
$\sigma_{control}$	= Control cavitation number at test section
σ_{local}	= Local cavitation number at pumpjet
σ_f , σ_{prop} & $\sigma_{prototype}$	= Full scale propeller cavitation inception number
σ_{ip}	= Propeller cavitation inception number
ρ	= Density of tunnel water, (kg /m³)

1. INTRODUCTION

Axi-symmetric underwater bodies are conventionally fitted with Contra-rotating Propellers (CRP), which consist of a forward and an aft propeller, working on coaxial contra-rotating shafts using the body wake as inflow and imparting momentum to the fluid to generate the required thrust. Efficiency of the propulsor is reasonably high in this case as the thrust is generated by two propellers. Cavitation performance is also superior compared to a single screw propeller as the thrust is distributed over more number of blades of the two propellers. Ideally there would be no rotation in the race behind the aft propeller and hence no residual torque and rotational moment of the body during its operation. It is, however, observed that as the body speed increases beyond 40 knots, cavitation poses serious problems; thus necessitating requirement of an alternate propulsor. One such alternative is a special propulsor, designed in a manner similar to an axial flow compressor with rotor and stator enclosed within a shroud. This special type of propulsor is called as Pumpjet Propulsor. Its decelerating cowl surrounding the rotor and stator, increases the static pressure of the fluid ahead of the rotor and thus delays the onset of cavitation on rotor.

Very limited information is available on pumpjet propulsor in open literature; further the published material is available in an assorted and disconnected manner. Thurston et al. [1] & [2] reported that jet efficiency values of well over 100% are attainable and as a result, values of propulsive efficiency approaching 100% are attainable. Thurston [3] reviewed the status of marine propellers and presented general operating regimes of the propellers. Wislicenus [4] reported that primary requirements of propellers viz., low machinery weight, good efficiency and good cavitation resistance are conflicting requirements. A method for pumpjet design was published by Henderson et al. [5] and they brought out various issues associated with the design and used improved NACA cascade data but did not include the influence of cowl on the performance. Vosper [6] reported that the British Royal Navy fitted their submarines with pumpjets. Vosper reported that American Sea-wolf submarine were also to be fitted with pumpjets. McCormik [7] studied the designs of contra-rotating propellers and pumpjets with reference to their efficiency and cavitation. McCornick et al. [8] have also published a comprehensive report on torpedo propellers including the manufacturing requirements. Markatos [9] carried out computational investigations of thick axisymmetric turbulent boundary layer and wake of bodies of revolution. Turbo-machinery principles, theory and design methods/calculations were published in a book by Wislicenus [10]. Das HN et al. [11] carried out CFD simulation of PJP using RANS through finite volume formulation using K-ε model and predicted the performance reasonably well, when compared to experimental results. Ivanell [12] carried out a detailed CFD simulation of flow over the torpedo and pumpjet jointly with SAAB Bofors Underwater Systems.

Suryanarayana et al. [15] published a performance evaluation technique for pumpjet through model testing in cavitation tunnel. NSTL, India set up a modern cavitation tunnel facility with a test section size of 1m x 1m x 6m exclusively for the development of naval vessels and their propellers; the facility details were published by Suryanarayana [16]. Suryanarayana [17] published a paper on the developments undertaken by NSTL on propellers for naval applications. Satyanarayana, et al. [18] reported the techniques employed in a wind tunnel at NSTL for investigations on torpedo hydrodynamics. He presented [19] a paper during National Science Day Celebrations on technological challenges encountered at NSTL in the development of advanced propellers for high speed marine vehicles. Further Suryanarayana [20] reported on the innovative techniques employed at NSTL for manufacture of propellers using computer aided machining (CAM). Keshi, et al. [21] presented a philosophy employed for the development of contra-rotating propellers for torpedo. Suryanarayana [22] reported the development of hydrodynamic profile and propellers for a decoy required to hover over a depth range and experimental technique employed for evaluation of performance using an instrumented decoy. Keller [23] [24] published new scaling laws for predicting cavitation inception. Joubert [25] reported the concepts essential for hydrodynamic design of a submarine. Suryanarayana et al. [26] presented a method for experimental evaluation of pumpjet in wind tunnel. Suryanarayana et al. [27] also published an experimental technique for performance evaluation of pumpjet through testing in a cavitation tunnel

Though the available literature is assorted, the author has undertaken a systematic study and developed a method for design and development of pumpjet. As part of this exercise a PJP was designed; its performance was predicted through CFD study and was subsequently manufactured for the Underwater Body. The propulsor design was evaluated for its propulsion characteristics through a series of model tests in Wind Tunnel. The concluding part of the study for the evaluation of the cavitation performance of the rotor, stator and cowl was undertaken in Cavitation Tunnel.

In order to assess the cavitation free operation speeds and depths of the body, it is required to determine the cavitation inception number for each element susceptible to cavitation. The most important element in this case is the rotor as the thrust developed may reduce appreciably if severe cavitation is present on it. Cavitation tests for the PJP were carried out in behind condition for a range of tunnel speeds and rotor RPS to determine the inception cavitation numbers for rotor, stator and cowl. This paper presents, in detail, the investigations undertaken on the pumpjet in CT elaborating the testing method employed, experimental results and their comparison with the design requirement and CFD predictions.

This investigation was undertaken to develop an innovative testing technique for the evaluation of pumpjet for its cavitation performance. The technique and the setup was successfully developed and validated through corroboration of the experiment and observed inception position and depth at 35 knots of design speed of the vehicle against the predicted inception depth through CFD solution.

2. AIM AND SCOPE OF WORK

The aim and scope of work of the tests are as follows:

- To develop an innovative technique and setup for evaluating cavitation performance of pumpjet.
- To conduct cavitation tests in behind condition and obtain cavitation inception numbers of rotor, stator and cowl.
- To analyse the results for finding cavitation inception depths for different operating speeds of the underwater vehicle.

3. MODEL TEST SETUP

3.1. BODY MODEL

Body and pumpjet models were developed using aluminium alloy materials for cavitation tests of the pumpjet designed for the underwater body. The main particulars of the body are as given below.

Length of the body	: 2920 mm
Diameter of the body	: 324 mm
Rotor diameter	: 220 mm
Vehicle speed	: 35 knots
Design advance co-efficient:	2.168

The general arrangement of the underwater body model fitted with PJP and fins is shown at Figure.1a & 1b

Figure. 1a: Axi-symmetric Body with Pumpjet

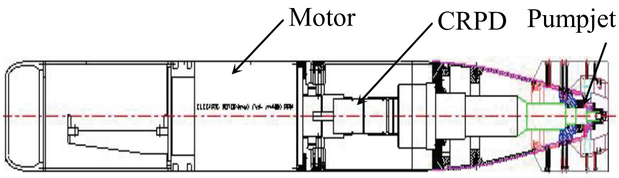

Figure. 1b: Schematic Diagram of Model Assembly

3.2. PUMPJET PROPULSOR

Pump-Jet Propulsor consists of a rotating vane system (rotor) and a stationary vane system (stator) operating within an axi-symmetric diverging and converging shroud (cowl). The stator is used to remove the swirl from the flow emanating from the rotor. The cowl retards the flow onto the rotor and provides an increase in static pressure and thereby delays cavitation.

The main particulars of the PJP are:

Rotor diameter	:	220 mm
Direction of rotation	:	Right Hand
No. of rotor blades	:	15
No. of Stator blades	:	21
Tip clearance	:	0.5 mm
Rotor hub diameter	:	110 mm
Duct profile	:	C4
Design RPM	:	2200

Configuration of the PJP is shown at Figure. 2. The cowl is an axi-symmetric body of revolution with hydrofoil cross section, surrounding both the rotor and the stator. For the purpose of observing cavitation of the blades in the tunnel, the cowl was manufactured out of transparent Perspex material. It can be seen that the forward propeller (rotor) blades are oriented in the clockwise direction viewed from aft while the aft propeller (stator) is in the opposite direction.

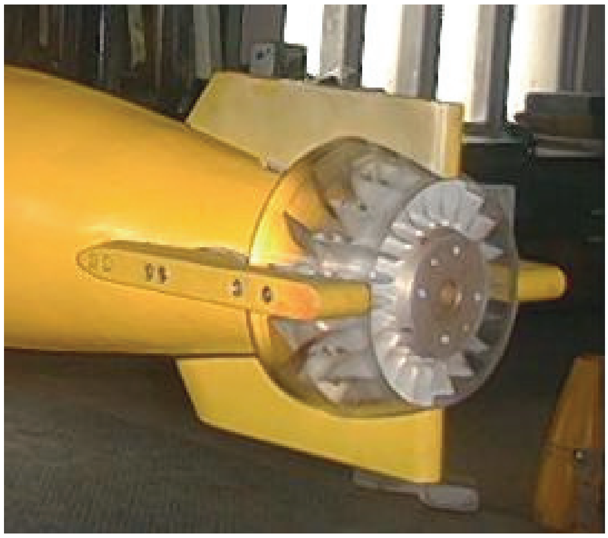

Figure. 2: PJP Fitted with Aft Body

3.3. MANUFACTURING PROCEDURE

A special aluminium alloy was used as per IS 734, grade 24345-1996 for manufacture of rotor and stator. Manufacture of these components has been undertaken with the help of numerically controlled milling machines to the desired dimensional accuracy and surface finish. The geometry was first modelled using CAM software and then fed to a five axis CNC machine to manufacture the components out of forged aluminium blanks. The components of the PJP were subjected to stringent inspection norms for dimensional tolerance, surface finish and dynamic balancing. Inspection of these components was carried out on 3-D Co-ordinate Measurement Machine (CMM) for confirming their geometrical accuracy.

4. **INSTRUMENTATION**

4.1. AUTOMATIC CONTROL SYSTEM (ACS)

The tunnel operation is fully controlled using an Automatic Control System (ACS), which regulates the set flow speed and pressure inside tunnel. The tunnel has a speed range of 0–15 m/s and a pressure range of 10–300 kPa absolute. The ACS with the help of various pressure sensors can obtain tunnel speed within ± 0.01m/s and pressure within ± 10 kPa accuracy. The ACS continuously monitors the health of various systems connected to it. In case of malfunctioning of any gauges/sensors, the ACS gives visual and audible alarms and in case of any emergency, it stops and shuts down the system and thereby preventing any permanent damage to the tunnel systems.

4.2. DATA ACQUISITION AND ANALYSIS SYSTEM (DAAS)

The Data Acquisition & Analysis System has been designed to carry out the various hydrodynamic tests accurately and record the test data. During the test of the model, the dynamometers which measure the forces and torques on the model and propellers are connected to the DAAS. The motor running the propellers is also connected to the DAAS. The flow parameters like speed, pressure, temperature etc., and the forces and torques from the dynamometers are recorded by the DAAS for each test condition. Apart from recoding the data from the dynamometers, the DAAS also continuously monitors the health of the dynamometers and other instruments connected to it. In case of any leak or overload, the DAS displays visual and audible alarms and thereby alerting the system operator to take corrective measures.

4.3. CONTRA-ROTATING PROPULSION DYNAMOMETER (CRPD)

Contra-rotating propulsion dynamometer is used for cavitation tests which consist of two coaxial shafts rotating in opposite directions, connected to a single shaft motor through a contra-rotating gear. The thrust and torque on each shaft are measured by variable inductive sensors. The main specifications of the dynamometer are as follows:

Thrust on each shaft	: ± 1500 N
Torque on each shaft	: ± 75 Nm
Permissible error	: ± 0.7% of max. load
Permissible mass of each propeller	: 3 kg

4.4. CUSTOMIZATION OF CRPD

CRPD is designed to operate with a pair of contra-rotating propellers. In this test, the aft propeller was stationary (stator). The tests necessitated careful planning to make use of CRPD as its outer shaft needed to be disengaged from the contra-rotating gear and ensuring at the same time that the forces and torques were transferred to the dynamometer sensing elements without any intermediate losses. Earlier attempts to use the Propulsion Dynamometer, Open Water Propeller Dynamometer, etc., in different combinations were not successful as it was difficult to analyse the influence of various flow obstructions caused by these dynamometers on the measured data. In this regard, the use of the CRPD with its outer shaft locked was considered to be suitable since it is fully enclosed by the model hull and able to simultaneously measure thrust and torque on both the shafts.

4.5. MOTOR AND FREQUENCY CONTROLLER

A motor along with a frequency controller was used to drive the propeller in the CT test section. The required RPS is set from the DAAS computer, which is communicated to the frequency controller. Precise RPS can be obtained with this setup from 0 – 60 RPS. Permissible error of RPS sensor is ± 1%

5. MODEL PREPARATION

The most important activity that affects the tests and the test data is the model preparation. The accuracy of the test data is dependent on the model preparation and hence extreme care is necessary during the model preparation and assembly. The preparation involves the following:

a. Mechanical jobs include manufacture and assembly of various components like the shell, struts, propulsor, dynamometer, etc. Figure. 3 indicates the model and CRPD during assembly. Figure. 4 shows the assembled model on test section cover.

b. Colouring of the rotor blades from the leading edge to 30% of chord is to ensure clear identification under stroboscopic light and visualization of cavitation inception conditions and extent.

Figure. 3: Body Model with CRPD

Figure. 4: Model of Body and PJP at CT

The model is held using two faired struts located in longitudinal central plane of the test section top surface. Dynamometers cables are routed through these struts from the model to a junction box located on top of the test section cover.

6. TEST FACILITY

The tests were conducted at the NSTL Cavitation Tunnel. Schematic diagram of the cavitation tunnel is given at Figure. 5. The salient features of this hydrodynamic test facility are as follows:

(i) Test section : 1 x 1x 6 m
(ii) Motor power : 700 kW DC
(iii) Max. test section velocity : 15 m/s
(iv) Pressure range (Abs) : 10-300 kPa
(v) Min. Cavitation No.: 0.08 - 37

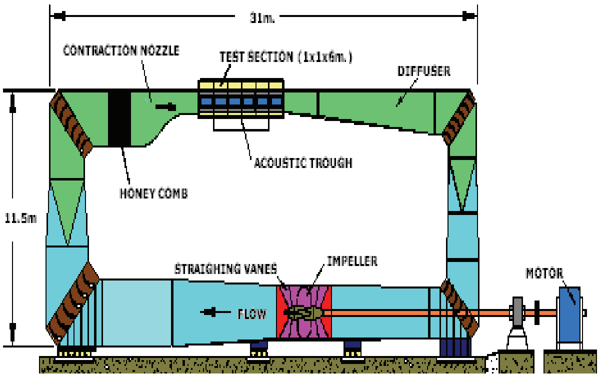

Figure. 5: Schematic Diagram of Cavitation Tunnel

7. TEST PROGRAMME

Tests were conducted at different flow speeds and advance ratios as per the test program given in Table.1 for obtaining the inception points on the rotor, stator and cowl separately. Tests at flow speed of 11 m/s were conducted only at the self propulsion region and tests at flow speeds 9 m/s & 10 m/s, were conducted over wider range of advance ratios.

Table 1: Test Program for Cavitation Tests

Tunnel Flow Speed	Speed: 8 m/s	Speed: 9 m/s	Speed: 10 m/s	Speed: 11 m/s
Advance Ratio (J)	**Rotor RPS (n)**	**Rotor RPS (n)**	**Rotor RPS (n)**	**Rotor RPS (n)**
1.8	20.2	-	-	-
1.9	19.14	-	-	-
2	18.18	20.45	22.72	25
2.1	17.32	19.48	21.64	23.80
2.2	16.53	18.6	20.66	22.72
2.3	15.81	17.79	19.76	-
2.4	15.15	17.04	18.94	-
2.5	14.55	16.36	18.18	-

8. TUNNEL PREPARATION

The cavitation tunnel needs to be prepared before commencing any experiment. Firstly, the fully assembled and inspected model is installed into the test section and the test section cover is tightly closed. Further, water is filled completely in the test section extending up to a height of approximately 1.5 m above the centre line of the test section in the intermediate tank. The cables are connected to the Data Acquisition & Analysis System through a junction box and once again all signals are checked and the water lines connected to the different pressure transducers that measure the flow velocity and pressure in the test section is flushed to remove entrapped air bubbles or other obstructions. Entrapped air in the test section is removed by applying high pressure in the intermediate tank and opening the test section vents. Once continuous water flows through vents without air bubbles are observed, the high pressure is released and the system is then ready for tests.

9. TEST PROCEDURE

The cavitation diagram is a plot of ($\sqrt{\sigma_i}$) against the Advance Ratio (J), where σ_i is the critical cavitation number at which the inception of propeller cavitation occurs. The Cavitation inception point is the instant when cavitation bubbles just start appearing on the surface of the element under study. The tunnel flow speed, static pressure at the tunnel reference point at the entrance of the test section, the local pressure i.e., from tunnel pressure tapping closest to the cavitating element and rotational speed (of propeller) are recorded at this precise instant through DAAS to determine the cavitation inception number which are defined as follows;

It is defined for free upstream condition

$$\sigma_i = [P_{ts}+P_a - P_v] / [\tfrac{1}{2} \rho V^2] \quad (1)$$

In case of a propeller

$$\sigma_{ip} = [P_l+P_a - P_v] / [\tfrac{1}{2} \rho (\pi n D)^2] \quad (2)$$

Flow speed at the test section is measured using differential pressure at contraction section at the test section inlet. Blockage worked out for the size of the current model is < 9% and no blockage corrections were suggested by the tunnel designer for cavitation studies. Tunnel pressure and atmospheric pressures are independently obtained by separate instruments and admissible inaccuracy of these instruments is < 0.1%. Overall maximum possible error of the non-dimensional numbers are also less than 1% due to measurement errors of various gauges used in the tunnel. Recommended air content to be maintained in tunnel water is 0.6 – 0.7 % of saturated air content for the cavitation tests. Degassing is carried out through application of vacuum at intermediate tank near the end of diffuser.

Cavitation tests are conducted at a fixed RPS of rotor and various advance coefficients. The minimum permissible propeller revolution was chosen so as to provide critical propeller Reynolds number i.e., 6 x 10^5 to avoid laminar effects on blades. For cavitation bucket tests, the normal practice is to first set the speed and RPS as required to obtain a pre-defined Advance Ratio (J) and then the pressure is lowered sufficiently until there is a clear visible cavitation on the propeller blade or appendage surface as the case may be. Once clear cavitation is observed, the test section static pressure is increased until the cavitation bubbles just reach the state of disappearance completely. At the instant cavitation is about to disappear, inception point is recorded as the cavitation inception point. This method of approaching the inception point by raising the pressure gives better control, which is essential as the recording point is solely decided by visual observation and hence it is liable to be highly subjective if the recording is done while cavitation is on the forming path. It is possible that in the case of a propeller, all the blades may not start cavitating simultaneously, which is the most common case. When majority of the blades start cavitating, it is usually considered as the cavitation inception point. The recording of inception point is dependent on the experience of the person conducting the experiment, availability of light, extent of de-aeration, presence/absence of cavitation from any other source etc. Hence the data scatter in these tests is likely to exist and usually an average value is found for each point after two or three repeats.

Acoustic Measurement System (AMS) incorporated with a hydrophone array available under the test section in CT is also used for recording cavitation inception in cases wherever necessary.

Model test results were extrapolated to full-scale conditions by calculating the critical rotation rate of the full scale propeller for each point on the left branch and right branch as suggested through empirical relations established using tests and trials over large vehicle data at reference (13) for propellers are given below:

$$n_f = \frac{1.57\,(10+h).n_m^{\,0.13}.D_m^{\,0.26}}{(\sqrt{\sigma_m})^{0.87}.\,D_f^{\,1.13}}$$

$$\sqrt{\sigma_f} = \frac{(\sqrt{\sigma_m}).(\,n_f.\,D_f^{\,2})^{0.15}}{(\,n_m.\,D_m^{\,2})^{0.15}}$$

10. CAVITATION INCEPTION ON PJP

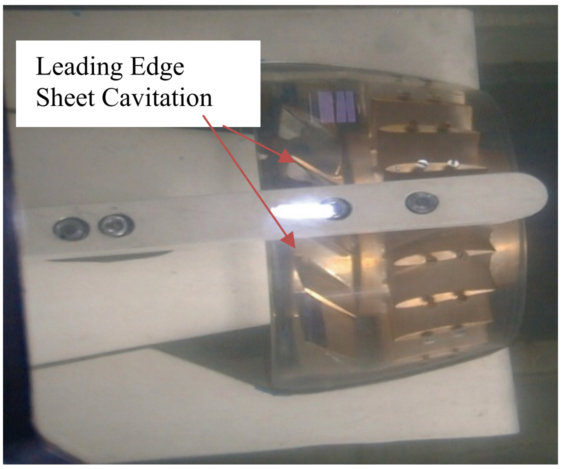

Figure. 6 : Cavitation on Rotor

Cavitation inception on the rotor was recorded for a range of J values at a constant tunnel speed of 10 m/s and 11 m/s and results are shown at Table 2. Photographs of the cavitation tests are given at Figure. 6 & 7. Tests at lower speeds i.e., 8 m/s and 9 m/s were not successful as the propeller Reynolds number at these speeds is less than the Critical Reynolds number required for containing the laminar flow effects. The test results of 10 m/s and 11 m/s were corrected for full scale Reynolds number and shown in Table 2 as Full Scale Cavitation Number.

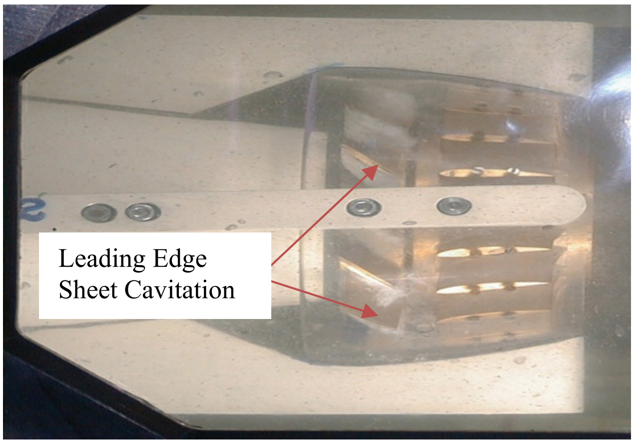

Figure. 7: Severe Cavitation on

Table 2: Cavitation Inception Test Results

Cavitation Inception on Rotor (Cycle 1)						
Flow Speed V, m/s	$\sigma_{control}$	σ_{local}	RPS	J	σ_m	σ_{proto} type
10.1	3.99	3.93	22.7	2.01	1.61	1.43
10	3.96	3.89	21.6	2.11	1.76	1.57
10	3.24	3.19	20.6	2.22	1.59	1.45
10	2.9	2.84	19.7	2.32	1.55	1.44
10	2.54	2.5	19	2.41	1.47	1.39
10	2.22	2.16	18.2	2.51	1.38	1.33
10.8	3.78	3.69	23.8	2.07	1.6	1.49
10.8	3.61	3.51	22.7	2.17	1.68	1.49
10.8	3.24	3.15	21.7	2.27	1.64	1.47
Cavitation Inception on Rotor (Cycle 2)						
Flow Speed V, m/s	$\sigma_{control}$	σ_{local}	RPS	J	σ_m	σ_{proto} type
10	3.99	3.89	22.7	2.01	1.6	1.43
10	3.92	3.86	21.6	2.12	1.75	1.56
10	3.29	3.22	20.6	2.22	1.6	1.46
10	2.78	2.72	19.7	2.31	1.47	1.37
10	2.62	2.57	19	2.41	1.51	1.42
10.1	2.1	2.07	18.2	2.51	1.32	1.36
10.9	3.22	3.12	21.7	2.27	1.63	1.47
10.8	3.45	3.35	23.7	2.08	1.47	1.47

Table 3: Cavitation Inception Numbers

J	σ_{prop}
2	1.506
2.1	1.478
2.168	1.459
2.2	1.450
2.3	1.423
2.4	1.396
2.5	1.369

Table 4: Cavitation Inception Numbers from Fit Curve

Cavitation Inception on Rotor (Averaged)			
Tunnel Flow Speed, V (m/s)	J	σ_{model}	$\sigma_{prototype}$
10.1	2.01	1.605	1.429
10	2.11	1.755	1.564
10	2.22	1.595	1.457
10	2.32	1.51	1.406
10	2.41	1.49	1.403
10	2.51	1.35	1.344
10.8	2.07	1.535	1.477
10.8	2.17	1.68	1.48
10.8	2.27	1.635	1.469

11. RESULTS AND DISCUSSIONS

11.1. ROTOR

During the cavitation inception tests, cavitation was noticed on the tip face at higher advance ratios and on leading edge suction side at lower advance ratios. Cavitation did not start on all the blades simultaneously, which is normal considering the fact that minute surface deviations from one blade to another may be present which cannot be quantified. The wake field is not uniform because of the presence of the model holding struts, the fins supporting the cowl and also due to the variation in static pressure as the blades makes a revolution. The cavitation inception was recorded for an average blade condition.

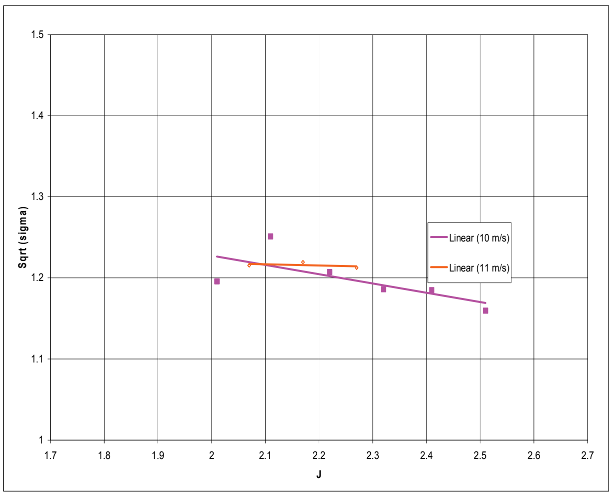

Figure. 8: Cavitation Diagram at 10 m/s and 11 m/s

The cavitation was initially observed towards the blade tip. The blade roots were free of any cavitation. As J was reduced by increasing the RPS, the inception number also reduced. For the complete range of J values from 2.51 to 2.01, the pattern observed was leading edge sheet cavitation always on the suction side, and its extent spreading from the tip towards root. Further at the lower J (high RPS) measured, the cavitation was seen extending over the full span and along the chord length.

During the entire range of the test program and over the range of advance coefficient 2.01 to 2.51, suction side leading edge cavitation was found incepting first on the rotor almost at the tip of the blade. However, cavitation was not observed on stator and cowl. The cavitation inception data obtained from the tests is scaled to prototype condition as suggested at section 9 and data is included at Table 2. This inception data is averaged on both the test cycle data and tabulated at Table 3. It is further plotted as cavitation diagram at Figure. 8 which depicts as left branch. Cavitation inception number for the propulsor is lifted from the scaled diagram (Figure. 8) for the design J = 2.168. It is analysed further and propulsor inception depth versus vehicle speed plot is obtained (Figure. 9) and tabulated at Table 5. Inception depth for the design speed was estimated as 27m through CFD and it is also indicated at Figure 9. It is required to note that the inception would occur at leading edge suction side at the blade tip as observed from the pressure contours on rotor blades (Figure 16).

It is important to note that the cavitation diagram is almost flat indicating that the propulsor is almost insensitive to wake variations which are highly essential for the intended application as it needs to switch over from an intermediate speed (25-27 knots) to high speed (30 knots) very quickly. It may be also noted that the inception depth varies with second degree of the speed as well as the propulsor rate of revolution.

Table 5: Cavitation Inception Depths Vs Vehicle

Vehicle Speed, kts	Rotor RPS	Inception Depth, m
20	21.58	6.56
25	26.96	15.84
27	29.12	20.14
30	32.35	27.19
34	36.67	37.76
40	43.14	56.08
50	53.92	93.23

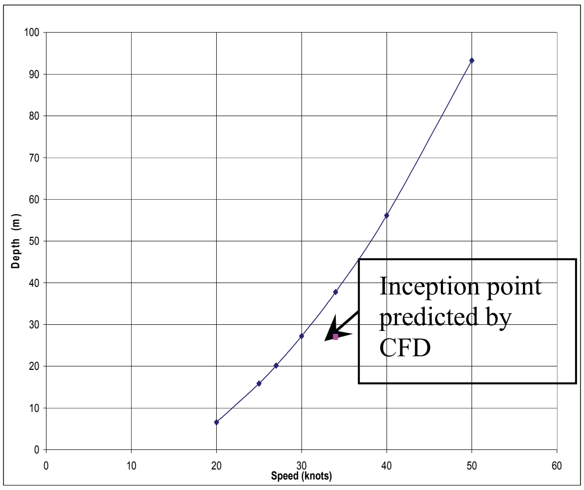

Figure. 9: Cavitation Inception Depth Vs Vehicle

11.2. COWL AND STATOR

There was no cavitation observed on the cowl and stator at any of the test conditions.

12. COMPARISON WITH CFD RESULTS

CFD analysis was carried out for propulsion (Ref. 11) and cavitation characteristics at the design speed and design RPM. The body fitted with the pumpjet was modelled (Figure. 10) using a CAD software and the solid model was imported to ICEM CFD using the inbuilt translators. A multi block structured grid was generated for the full body with pumpjet using ICEM CFD Hexa module. The grid generated by the hexa pre processor was exported to fluent solver. The flow domain was divided into three volumes and meshed separately. A unified mesh was exported from ICEM CFD to FLUENT. The segregated solver of FLUENT 6.2 was used for the solution. The Reynolds Time Averaged Navier-Stokes equations were framed for each control volume in the discretised form. The standard scheme is used for pressure and a SIMPLE (Strongly Implicit Pressure Link Equations) procedure is used for calculation of pressure field from the continuity equation. Computations were carried out for propulsion and cavitation performances using eight processor SGI Altix machine.

A solution was obtained for five different RPMs i.e., 0, 200, 500, 1000 and 2200. Figure. 11 and 12 indicate the pattern of flow lines on and behind the pumpjet for design RPM 2200. The flow within the PJP can be visualized through these plots. The thrust and torque generated by the PJP are plotted in Figure. 13 and 14. The pressure distribution on body, rotor and stator are shown in Figure.15 and 16. Figure. 13 shows that the computed drag and thrust are very close to the experimental drag and design thrust respectively. Figure. 14 as well indicates that the computed torque and design torque are also very close. Figure 17 indicates pressure profile on tip section (95% of span) where cavitation inception is likely at leading edge back side at design condition. Computed drag, thrust and torque values are shown in Table 6.

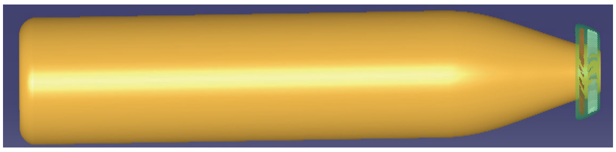

Figure. 10: Body Model with Pumpjet

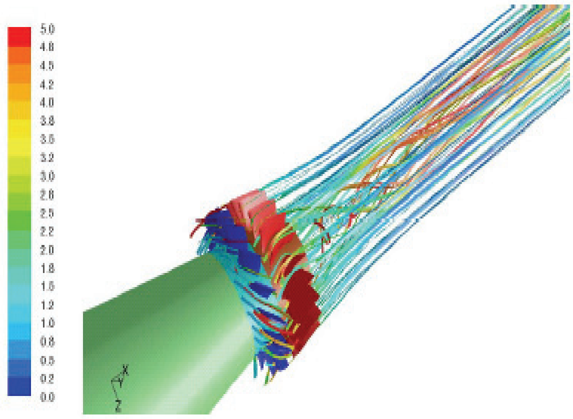

Figure. 11: Flow through Rotor and Stator

Table 6: Propulsive Performance of PJP

RPM	Drag of bare hull (N)	Thrust (N)	Torque (N-m)
0	1247.8	-762	-51.5
200	1585.3	-217	-16.3
500	1570.8	72	-1.1
1000	1560.3	359	26.7
2200	1500.8	1991	176

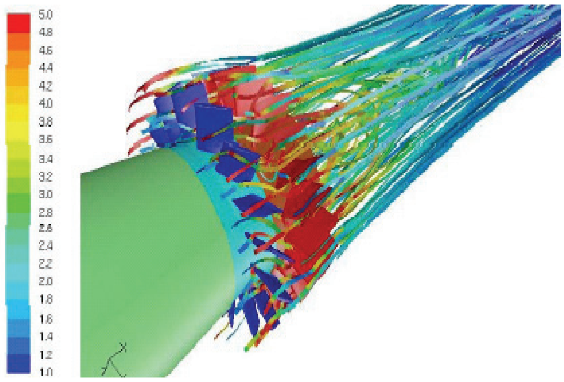

Figure.12: Flow through Rotor & Stator Blades (close-up)

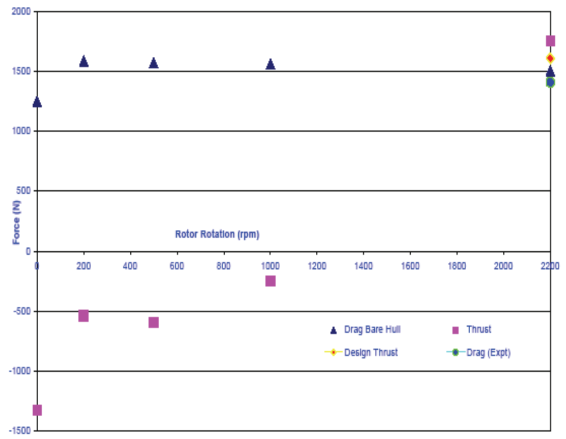

Figure. 13: Comparison of Thrust on

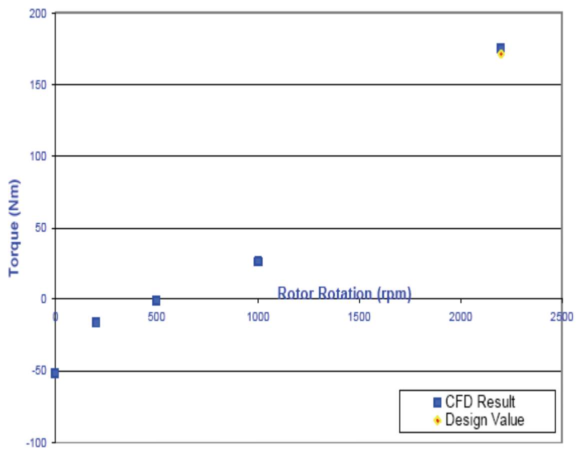

Figure. 14: Comparison of Torque on Rotor

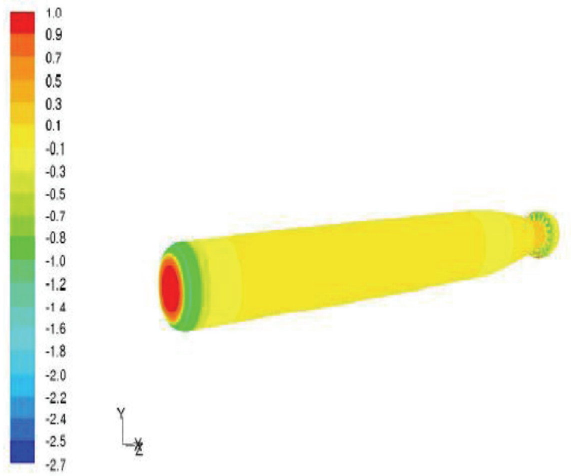

Figure. 15: Pressure Distribution on the Body

It is pertinent to emphasize that the position of cavitation inception found through tests and CFD predictions are close. Further the agreement of the inception depth from tests and CFD is also reasonably good while considering the influence of water quality and limitations of simulation of viscous effects in CFD analysis.

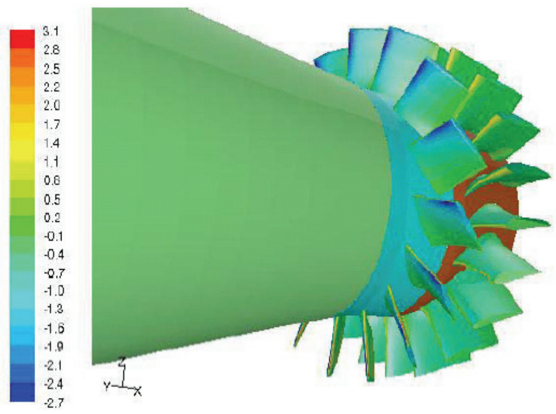

Figure 16. Pressure contours on Blades

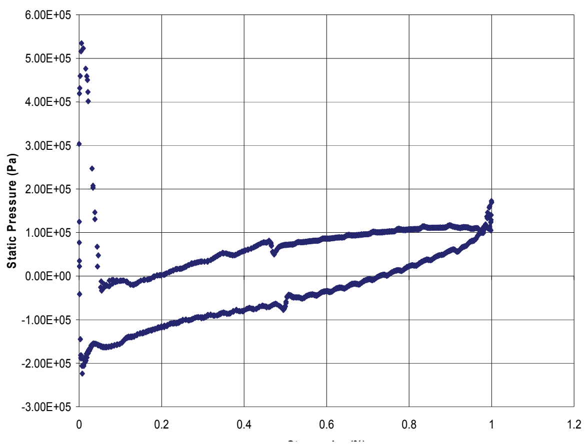

Figure. 17: Pressure Profile on Rotor Section (95 % span)

13. CONCLUSIONS

Based on the outcome of the experimental results of the investigations and comparison with the design data and CFD analysis of the design the following conclusions are drawn on the cavitation performance of the pumpjet:-

(a) Cavitation inception depth of PJP is found to be 37m at design speed of 35 knots.

(b) At the self propulsion point and very low cavitation numbers, the rotor cavitates on suction side and the cavity extends fully on the blade from tip to root all along the span. This observation confirms that the pumpjet is fully adapted for the wake.

(c) Cavitation inception on the rotor of the pumpjet propulsor takes place on the tip face side at higher advanced ratios and cavitation shifts towards the suction side.

(d) Cavitation inception occurs on the rotor at an acceptable depth when the vehicle operates at the design speed. Comparison of the experimental results with CFD results indicates good agreement with respect to inception position, depth and speed

(e) Stator and cowl will be free from cavitation over the operating envelop of the vehicle.

(f) These investigations facilitated the development of a method/technique for testing of pumpjet propulsor for evaluation of its cavitation performance.

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