Cavitation studies on axi-symmetric underwater body with pumpjet propulsor in cavitation tunnel

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ABSTRACT: A pumpjet propulsor (PJP) was designed for an underwater body (UWB) with axi-symmetric configuration. Its performance was predicted through CFD study and models were manufactured. The propulsor design was evaluated for its propulsion characteristics through model tests conducted in a Wind Tunnel (WT). 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 operation speeds and depths of the body, cavitation tests of the PJP were carried out in behind condition to determine the inception cavitation 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. From 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 RPS increases whereas the stator and cowl are free from cavitation.

KEY WORDS: Pumpjet; Cavitation; Cavitation tunnel; Propulsion; Experimental techniques; Hydrodynamics.

NOTATION

D : Propeller diameter, (m)
 D_f : Full scale propeller diameter, (m)
 D_m : Model scale propeller diameter, (m)
 h : Propeller axis submergence, (m)
 J : Advance coefficient
 P_{ts} : Test section static pressure, (Pa)
 P_l : Local static pressure at cavitating element, (Pa)
 P_a : Atmospheric Pressure, (Pa)
 P_v : Saturation vapor pressure, (Pa)
 n : Propeller revolutions per second, (RPS)
 n_f : Full scale propeller critical speed (RPS)
 n_m : Model propeller, (RPS)
 V : Tunnel flow speed, (m/s)
 R_n : Propeller Renolds Number
 σ_i : Cavitation inception number
 σ_m : Model propeller cavitation inception number
 σ_{contl} : Control Cavitation number at test section
 σ_{local} : Local cavitation number
 σ_f : Full scale propeller cavitation inception number
 σ_{ip} : Propeller cavitation inception number
 ρ : Density of tunnel water, (kg /m³)

INTRODUCTION

Axi-symmetric underwater bodies are conventionally fitted with Contrarotating Propellers (CRP), which consist of a forward and an aft propeller, working on coaxial contra-turning shafts using the body wake as inflow and imparting momentum to the fluid to generate the required thrust. Efficiency of the propulsor is high as the thrust is generated by two propellers and 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 movement 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 the requirement of alternate propulsors. 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 the Pumpjet Propulsor (PJP). It's decelerating cowl surrounding the rotor and stator which increases the static pressure of the fluid at the rotor position and thus delays the onset of cavitation on the rotor.

Very limited information is available on pumpjet propulsor in open literature. Thurston, and Evanbar (1965) reported that jet efficiency values of well over 100% are

attainable and as a result, values of propulsive efficiency approaching 100% are attainable. Thurston and Ansler (1966) revived the status of marine propellers and presented general operating regimes of the propellers. Wislicenus and George (1960) reported in 1960 that primary requirements of propellers viz., low machinery weight, good efficiency and good cavitation resistance are the conflicting requirements. A method for pumpjet design was published by Henderson et al. (1964) and they brought out various issues associated with the design and used improved NACA cascade data but not included the influence of cowl on the performance. Vosper and Brown (1996) reported that UK fitted their submarines with pumpjets. It was also reported that American Sea-wolf submarine was to be fitted with pumpjet. Mc. Cormick et al. (1956) studied the designs of contrarotating propellers and pumpjets with reference to their efficiency and cavitation. Mc. Cormick et al. (1956) have published a comprehensive report on torpedo propellers including the manufacturing requirements. Markatos (1984) carried out computational investigations of thick axisymmetric turbulent boundary layer and wakes of bodies of revolution. Turbo-machinery principles, theory and design calculations were published in a book by Wislicenus (1965). Das et al. (2006) carried out CFD simulation of PJP using RANS through finite volume formulation using $k-\varepsilon$ model and predicted the performance reasonably well comparable with experimental results. Stefan (2001) carried out a detailed CFD simulation of flow over the torpedo and pumpjet jointly with SAAB Bofors Underwater Systems.

Suryanarayana et al. (2006) 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 and the facility details were published by Suryanarayana et al. (2002). Suryanarayana et al. (2002) published a paper on the developments undertaken by NSTL on propellers for naval applications. Suryanarayana et al. (2002) reported the techniques employed in a wind tunnel at NSTL for investigations on torpedo hydrodynamics. He presented Suryanarayana (2004) 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 he reported Suryanarayana (2003) on the innovative techniques employed at NSTL for manufacture of propellers using computer aided machining (CAM). Suryanarayana et al. (2002) presented a philosophy employed for the development of contra-rotating propellers for torpedo. Suryanarayana et al. (2006) 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 (1994, 2000) published new scaling laws for predicting cavitation inception. Joubert (2004) reported the concepts essential for hydrodynamic design of a submarine. Suryanarayana et al. (2010) presented a method for experimental evaluation of pumpjet in wind tunnel. Suryanarayana et al. (2010) also published an

experimental technique for performance evaluation of pumpjet through testing in a cavitation tunnel.

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.

AIM AND SCOPE OF WORK

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

- To conduct cavitation tests in behind condition at different tunnel speeds and rotor rps to obtain cavitation inception numbers of rotor, stator and cowl.
- To analyse the results for cavitation inception depths for different operating speeds of the underwater weapon.

MODEL TEST SETUP

Body model

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

Table 1 Main particulars of the model.

Length to diameter ratio of body	8.61
Propeller (Rotor) Diameter	220 mm
Rotor Direction	Clockwise when viewed from body aft.

The general arrangement of the model fitted with PJP and fins is shown at Fig.1.

Fig. 1 Schematic diagram of model test assembly.

Pumpjet propulsor

Main Particulars

PJP consists of a rotating vane system (rotor) and a stationary vane system (stator) operating within an axis-symmetric diverging 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 thereby delaying cavitation. The main particulars of the model PJP are given below:

Table 2 Main particulars of PJP.

Direction of rotation	Clockwise
Scale	1: 1
Stator to rotor blade ratio	1.6
Propulsor diameter [mm]	220
Cowl length [mm]	125

Configuration of the PJP is shown at Fig. 2. Stator blades are oriented in the counter clockwise direction when viewed from the aft. The cowl is an axis-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 clearly 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.

Fig. 2 PJP fitted with body.

Manufacturing procedure

The manufacturing process of the different components of the PJP was subject to stringent inspection norms for tolerance, surface finish and dynamic balancing to meet best standards. A special aluminum alloy was used as per IS 734, GR 24345-1996 (HF15) standard for manufacture of rotor and stator. Manufacture of these components has been undertaken with the help of numerically controlled milling machines from a single block to the desired dimensional accuracy and surface finish. The geometry was first modeled using CAM software and then fed to a five axis CNC machine to manufacture the components out of forged aluminum blanks. Inspection of these components was carried out on 3-D Co-ordinate Measurement Machine for establishing their geometrical accuracy.

INSTRUMENTATION

Automatic control system (ACS)

The tunnel operation is fully controlled using the Cavitation Tunnel Automatic Control System (ACS) which regulates the set speed and pressure inside the test section. The tunnel has a speed range of 0~15m/s and a pressure range of 0~300kPa absolute. The ACS with the help of various pressure sensors can obtain set speeds within $\pm 1\text{cm/s}$ and set pressures within $\pm 10\text{kPa}$ 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 an emergency, it stops and shuts down the system thereby preventing any permanent damage to the tunnel system.

Data acquisition and Analysis system

The Data Acquisition & Analysis System (DAS) 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 DAS. The motor running the propellers is also connected to the DAS. The flow parameters like speed, pressure, temperature etc., and the forces and torques from the dynamometers are recorded by the DAS for each test condition. Apart from recoding the data from the dynamometers, the DAS also continuously monitors the health of the dynamometers and other instruments connected to it. In case of any leak or overload, the DAS gives visual and audible alarms and thereby alerting the system operators to take corrective measures.

Contrarotating propulsion dynamometer (CRPD)

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

Table 3 Main specifications of the dynamometer.

Thrust on each shaft	$\pm 1500\text{N}$
Torque on each shaft	$\pm 75\text{Nm}$
Permissible error	$\pm 0.7\%$ of max. load
Permissible mass of either propellers	3Kg
Propellers to be statically balanced	

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.

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 DAS computer, which is communicated to the frequency controller. Precise RPS can be obtained with this setup from 0~60RPS.

MODEL PREPARATION

The 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:

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

Fig. 3 Body model showing CRPD.

Fig. 4 Assembled model of body and PJP.

The model is held using two faired struts located in longitudinal central plane of the test section top surface. All dynamometer and electric cables are routed through these struts from the model to the connection box located on top of the test section cover.

TEST FACILITY

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

Table 4 Features of the test facility.

Test Section	$1 \times 1 \times 6 \text{ m}$
Motor Power	700 KW DC
Max Test Section Velocity	15 m/s
Pressure Range (Abs)	$0.1 \sim 3.0 \text{ Kg/cm}^2$
Min Cavitation No.	0.08 ~ 37 at Test Section

TEST PROGRAMME

Tests were conducted at different flow speeds and advance ratios as per the test programme given in Table 5 for obtaining the inception points on the rotor, stator and cowl separately. Tests at 11m/s flow speed were conducted only at the self propulsion region and tests at 9m/s, 10m/s flow speed, were conducted over wider range of advance ratios.

Table 5 Test programme.

Tunnel Flow Speed	Speed: 8m/s	Speed: 9m/s	Speed: 10m/s	Speed: 11m/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	-

Fig. 5 Schematic diagram of NSTL cavitation tunnel.

TUNNEL PREPARATION

The cavitation tunnel needs to be prepared before commencing an 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 1.5m above the centre of the test section in the intermediate tank. The cables are connected to the Data Acquisition and Analysis System through a junction box and once again all signals are checked. The water lines connected to the differential pressure transducers that measure the flow velocity and pressure in the test section are 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 flow without air bubbles is observed, the high pressure is released and the system is then ready for tests.

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 to determine the cavitation inception number which is defined as

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

It is defined as in the case of a propeller

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

Cavitation bucket 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 Reynolds number of propeller i.e., 6×10^5 to avoid laminar effects on blades. In cavitation bucket tests, the normal practice is to first set the speed and RPS as required to obtain a pre-defined Advance Ratio and then the pressure is lowered sufficiently till there is clearly visible cavitation on the propeller blade or appendage surfaces as the case may be. Once clear cavitation is observed, the test section static pressure is increased till 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 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.

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 branches as suggested at reference (KSRI, 2001) for propellers(3,4).

Where,

$$n_f = \frac{1.57 \cdot (10 + h) \cdot n_m^{0.13} \cdot D_m^{0.26}}{(\sqrt{\sigma_m})^{0.87} \cdot D_f^{1.13}} \quad (3)$$

$$\sqrt{\sigma_f} = \frac{(\sqrt{\sigma_m}) \cdot (n_f \cdot D_f^2)^{0.15}}{(n_m \cdot D_m^2)^{0.15}} \quad (4)$$

CAVITATION INCEPTION ON PJP

Cavitation inception on the rotor was recorded for a range of J values at a constant tunnel speed of 10m/s and 11m/s and results are shown at Table 6. Photographs of the cavitation tests are given at Fig. 6 & Fig. 7. Tests at lower speeds i.e., 8m/s and 9m/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 10m/s and 11m/s were corrected for full scale Reynolds number and shown in Table 6 as Full Scale Cavitation Number.

Fig. 6 Rotor cavitation at 10m/s.

Fig. 7 Severe cavitation on rotor.

Table 6 Test results.

Cavitation Inception on Rotor (cycle 1)						
Tunnel Flow Speed, V (m/s)	$\sigma_{control}$	σ_{local}	RPS	J	σ_{model}	Reynolds number corrected, $\sigma_{prototype}$
10.1	3.99	3.93	22.7	2.01	1.61	1.433
10	3.96	3.89	21.6	2.11	1.76	1.568
10	3.24	3.19	20.6	2.22	1.59	1.452
10	2.9	2.84	19.7	2.32	1.55	1.438
10	2.54	2.5	19	2.41	1.47	1.387
10	2.22	2.16	18.2	2.51	1.38	1.327
10.8	3.78	3.69	23.8	2.07	1.6	1.488
10.8	3.61	3.51	22.7	2.17	1.68	1.487
10.8	3.24	3.15	21.7	2.27	1.64	1.473
Cavitation Inception on Rotor (cycle 2)						
Tunnel Flow Speed, V (m/s)	$\sigma_{control}$	σ_{local}	RPS	J	σ_{model}	Reynold number corrected, $\sigma_{prototype}$
10	3.99	3.89	22.7	2.01	1.6	1.425
10	3.92	3.86	21.6	2.12	1.75	1.561
10	3.29	3.22	20.6	2.22	1.6	1.462
10	2.78	2.72	19.7	2.31	1.47	1.374
10	2.62	2.57	19	2.41	1.51	1.419
10.1	2.1	2.07	18.2	2.51	1.32	1.361
10.9	3.22	3.12	21.7	2.27	1.63	1.465
10.8	3.45	3.35	23.7	2.08	1.47	1.466

Table 7 Inception numbers averaged.

Cavitation Inception on Rotor (Averaged)			
Tunnel Flow Speed, V (m/s)	J	σ_{model}	Reynolds number Corrected, $\sigma_{prototype}$
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

RESULTS AND DISCUSSIONS

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 make a revolution. The cavitation inception was recorded for an average blade condition.

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

A plot of the inception point against J is given in Fig.8. The plot appears as the left branch of a typical cavitation bucket diagram, with linear variation. The data scatter is in expected lines considering the fact that the rotor of the pump jet has more blades unlike a conventional propeller. Table 8 gives the averaged cavitation inception numbers from the straight line fit of the experimental data.

The averaged cavitation inception number for the rotor computed for self propulsion advance ratio ($J=2.168$) was analysed for inception depths at different operating speeds and is shown in Table 9.

Fig. 8 Cavitation diagram for 10m/s and 11m/s flow speed.

Table 8 Inception numbers from fit curve.

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 9 Inception depths for different speeds.

Vehicle Speed <i>kts</i>	Rotor RPS	Inception Depth <i>m</i>
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

Fig. 9 Cavitation inception depths for rotor for different speeds.

Cowl and Stator

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

COMPARISON WITH CFD RESULTS

CFD analysis was carried out for propulsion and cavitation characteristics at the design speed and rpm. The body fitted with the pumpjet was modeled using CATIA 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. An 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. The pressure distribution computed, on rotor at 95 % of span was plotted considering the atmospheric pressure as reference pressure and shown in Fig.11 From the Figure, it is found that the rotor cavitates at 27 m depth as the lower pressure computed was ~2.7 bar at 10% of the chord. CFD results are compared with experimental results and plotted at Fig.9.

Fig. 10 Rotor and stator pressure contours.

Fig. 11 Pressure distribution on rotor blade at 95% span.

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 have been drawn on the cavitation performance of the pumpjet:

- Cavitation inception on the rotor of the pumpjet propulsor takes place on the tip face side at higher advance ratios and cavitation shifts towards the suction side. 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.
- 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.

- Stator and cowl will be free from cavitation over the operating envelop of the vehicle.
- These investigations facilitated the development of a method/technique for testing of pumpjet propulsor for evaluation of its cavitation performance.

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