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Torque Balance And Cavitation Studies On Underwater Vehicle Propulsion System

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Abstract:

Cavitation is the prime enemy for high speed underwater vehicles, which limits the vehicle speed and effect on its efficiency in terms of speed, power and noise. Conventional propellers fail to generate the thrust required to propel the vehicle beyond certain speeds due to onset of cavitation. To overcome the limitations imposed by conventional propellers, the state of the art Pumpjet propulsion system is being used for high speed underwater vehicles. A Pumpjet propulsor has been designed for high speed underwater vehicle, validated its performance through model tests at hydrodynamic test facilities. Propulsion tests are conducted at High Speed Towing Tank to estimate the power delivered for different operating speeds. Torque balance tests and cavitation tests are conducted at Cavitation Tunnel to estimate the imbalance torque between rotor and stator and cavitation inception depths of Pumpjet propulsor for different operating speeds. The present paper describes in detail about the cavitation performance of Pumpjet propulsor, imbalance torque between rotor and stator and correction methods adopted for improving its performance.

Key words: *Pumpjet, Cavitation, Torque Balance*

1. Introduction

Cavitation on propellers limits the vehicle speed and effect on its efficiency in terms of speed, power and noise. To avoid cavitation and achieve desired speed within the budgeted power and contented radiated noise is a exigent job for the designer. Conventional propellers are being used for high speed underwater vehicles considering wake adoption, large propeller diameter, higher blade number and uniform sections, but as the demand for speed increases beyond certain speeds, these propellers fail to operate due to onset of cavitation. State of the art Pumpjet propulsion system has been developed to overcome the limitations imposed by conventional propellers. A Pumpjet propulsor has been designed for high speed underwater vehicle, evaluated its performance through CFD analysis and developed the models to validate the design through model tests at hydrodynamic test facilities. Propulsion tests are conducted at High Speed Towing Tank to evaluate its propulsive performance and estimate the power delivered for different operating speeds. Torque balance tests and cavitation tests are conducted at Cavitation Tunnel to estimate the imbalance torque between rotor and stator and cavitation inception depths of Pumpjet propulsor for different operating speeds. Torque imbalance of about 19-22 % was predicted between rotor and stator at all the advance coefficients, and it was corrected experimentally by varying the stator pitch angles as the rotor of the Pumpjet propulsor is generating the thrust required to propel the vehicle at the desired speed. Further cavitation performance of the Pumpjet propulsor was evaluated and predicted the inception speeds for different operating depths. The present paper describes in detail about the cavitation performance of Pumpjet propulsor, imbalance torque between rotor and stator and correction methods adopted for balancing the torque.

2. Pumpjet Propulsor Overview

Pumpjet propulsor consist of a rotor, stator and an axi symmetric cowl. Pumpjet propulsor with post swirl stator was designed for high speed underwater vehicle with best possible cavitation performance and minimal imbalance torque at all the advance coefficients. Longer cowl is considered in the design for high diffusion rates and enhanced cavitation performance. Resistance and velocity profile at rotor plane were generated from model tests at wind tunnel and CFD studies and it was used to optimize the rotor diameter by means of computing mass flux, inlet momentum, outlet momentum and efficiency at different radii. Pumpjet design was carried out for optimum diameter considering velocity profile at rotor plane and design correlation charts. CFD analysis has been carried out to evaluate the design with respect to propulsion and cavitation performance. Strength analysis was carried out by applying hydrodynamic loads and concluded that the stress levels and deflections are within the acceptable limits. Full scale Pumpjet model was developed to integrate with the underwater vehicle and carryout model tests at hydrodynamic test facilities to validate the design with respect to propulsive performance, cavitation performance and torque balance.

3.Test Facility And Model Test Setup

Tests were conducted at NSTL Cavitation Tunnel using full-scale underwater vehicle model fitted with Pumpjet propulsor. NSTL Cavitation Tunnel is a closed circuit tunnel in which the pressure in the test section can be varied from 2 bar gauge pressure to 90 kPa vacuum and velocity can be varied from 0 m/s to 15 m/s. Model was equipped with a Contra-Rotating Propulsion Dynamometer (CRPD) which consist of two coaxial shafts rotating in opposite direction with individual motors and the shafts were instrumented with strain gauges to measure thrust and torque of propellers connected to it. In this configuration, rotor of the Pumpjet was connected to inner shaft and stator along with the cowl and control surfaces was connected to outer shaft and locked. The model was fitted to the test section cover using two faired struts located longitudinally along the center 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.

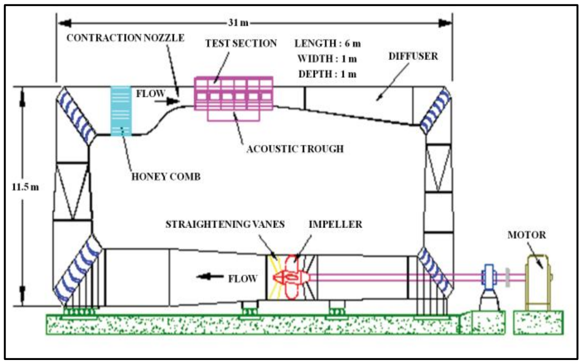

Figure 1: Schematic of NSTL Cavitation Tunnel

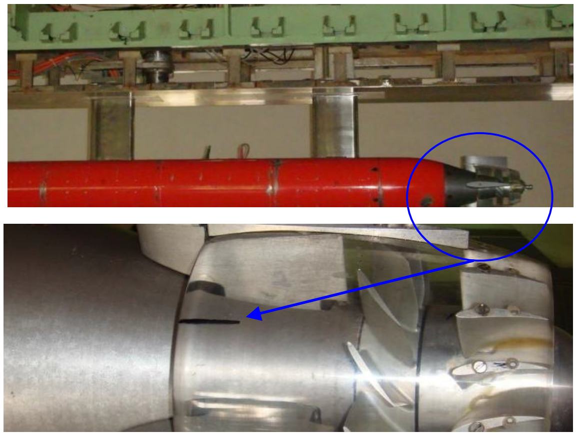

Figure 2: Underwater Vehicle and Pumpjet Models

4.Test Matrix

Model tests at cavitation tunnel were conducted in two phases, in the first phase torque balance tests were conducted to estimate the imbalance torque between rotor and stator and correct the imbalance torque experimentally if required. In the second phase cavitation tests were conducted to estimate the cavitation inception depths of the Pumpjet elements at different operating vehicle speeds.

4.1.Torque Balance Tests

Torque balance tests were conducted at constant tunnel speed ranging from 4 m/s to 7m/s @ 1 m/s and different advance coefficients ranging from 1.7 to 2.5 by varying rotor RPS considering the dynamometer limitations. Though the tests were conducted for different speeds, results of 6 m/s tunnel speed only is presented in the present paper to avoid the cluster of data and data misinterpretation.

4.2.Cavitation Tests

Cavitation tests were conducted to determine the cavitation bucket of the rotor and study the cavitation pattern at both design and off design conditions. Tests were conducted at constant RPS and different advance coefficients by varying tunnel speed ensuring the critical Reynolds number and No laminar effects. Subsequently tests were also conducted at 6 m/s and 7 m/s tunnel speed and different advance coefficients ranging from 1.7 to 2.5 considering dynamometer limitations by varying rotor RPS. At each test condition cavitation inception pressure of stator and cowl were recorded independently and non-dimensionalised to obtain the cavitation diagram and also to establish the influence of rotor RPS on cavitation performance of stator and cowl.

5. Model Test Results And Discussions

5.1.Torque Balance Tests

Torque on the rotor and stator of the Pumpjet propulsor was measured independently at 6 m/s tunnel speed and different advance coefficients by varying rotor RPS. Torque measured was non-dimensionalised with respect to rotor RPS and diameter to obtain the torque coefficient Kq and plotted against the advance coefficient (J) and shown in Figure 3. Though the torque on the rotor and stator are opposite in sign to control the rolling moment of the vehicle, for comparison of values and representation in the graphs absolute values only are considered. Where

$$K_q = \frac{Q}{\rho n^2 D^5} \qquad J = \frac{V}{nD}$$

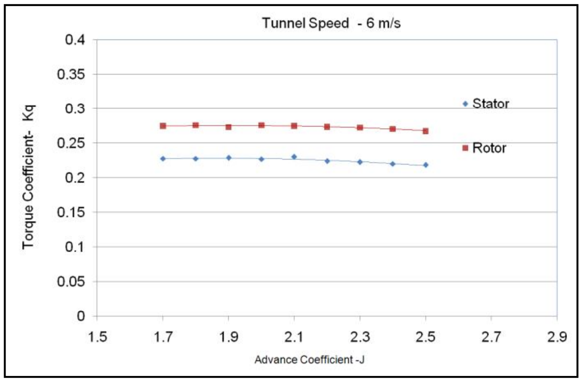

Figure 3: Torque Imbalance of Pumpjet

From the results it is observed that the torque on the rotor was 19-22 % more than the stator. So it was decided to balance the torque by increasing the stator pitch angles without disturbing the rotor as it was generating the thrust required to propel the vehicle at designed speed.

5.1.1.Stator with Detachable Blades

In order to manufacture the number of stators with different pitch angles, which was more time consuming and huge cost involved, it was decided to manufacture detachable stator blades, stator hub and holding rings to assemble the stator blades at increased pitch angles and correct the imbalance torque experimentally. Holding rings were manufactured with angular slots ranging from 1 deg to 6 deg to increase the pitch angle @ 1 deg. Tests were repeated with stator fitted with 4 deg, 5 deg and 6 deg ring and measured the torque imbalance of the Pumpjet Propulsor.

Figure 4: Detachable Blades & Holding Ring

From the results it was observed that the torque imbalance of the Pumpjet was reduced with the increase of the stator pitch angle. Torque of the rotor was 1-3 % more than the stator torque with 5 deg increased pitch angle whereas with 6 deg increased pitch angle, the stator torque was 2-6 % more than the rotor torque. Graph was drawn between maximum % of imbalance torque and increased pitch angle and concluded that at 5.4 Deg increased stator pitch angle, zero imbalance torque of the Pumpjet may be achieved. These modifications were incorporated in the design and manufactured the stator with fixed blades, repeated the tests and confirmed the torque balance of the Pumpjet.

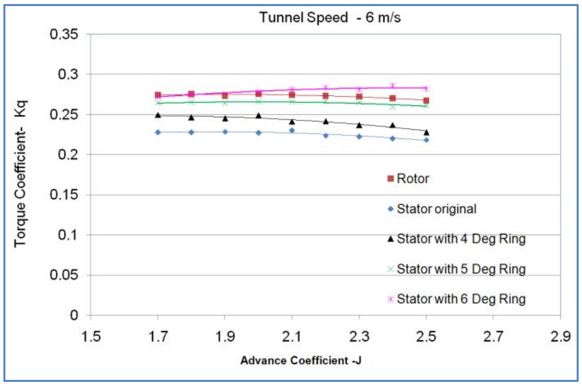

Figure 5: Torque Imbalance with Increased Stator Pitch Angles

	Torque Coefficient (Kq)				
Advance Coefficient	**Rotor**	**Stator**	**Stator with Increased Pitch Angle By**		
J			**4 Deg**	**5 Deg**	**6 Deg**
2.5	0.267	0.218	0.228	0.262	0.282
2.4	0.270	0.220	0.237	0.259	0.286
2.3	0.272	0.223	0.237	0.265	0.281
2.2	0.273	0.224	0.242	0.267	0.284
2.1	0.275	0.230	0.241	0.266	0.281
2	0.276	0.227	0.249	0.266	0.278
1.9	0.273	0.229	0.245	0.264	0.279
1.8	0.276	0.228	0.247	0.266	0.274
1.7	0.275	0.228	0.250	0.265	0.273

Table 1: Torque Coefficient of Rotor and Stator

5.2.Cavitation Tests

Cavitation tests were conducted to determine the cavitation inception number and cavitation pattern on the Pumpjet elements at both design and off design conditions. During the tests, speed of the tunnel and rotor RPS was set as required and the pressure is lowered sufficiently till there is clearly visible cavitation on the Pumpjet elements. Once clear cavitation is observed, the test section static pressure is increased till the cavitation bubbles disappear completely. The instant the cavitation is about to vanish is recorded as the cavitation inception point for each Pumpjet element independently. This method of approaching the inception point by raising the pressure gives better control, which is essential as the recoding point is solely decided by visual observation and hence it is liable to be highly subjective. It is possible that in the case of rotor not all blades start cavitating simultaneously, which is the most common case. When majority of the blades start cavitating, it is usually considered the cavitation

inception point. Recording of inception point is dependent on the experience of the person conducting the experiment, availability of light, extent of deaeration, presence/absence of cavitation from any other source etc. Hence the data scatter in these tests are likely to be more and usually an average value is found for each point after two or three repeats. Cavitation inception point is the instant when cavitation bubbles 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 the rotor are recorded at this precise instant, to determine the cavitation inception number which is defined as.

$$\sigma_i = \frac{P_{ts} + P_a - P_v}{\frac{1}{2}\rho V^2}$$

and in the case of rotor as

$$\sigma_{ip} = \frac{P_l + P_a - P_v}{\frac{1}{2}\rho(\pi n D)^2}$$

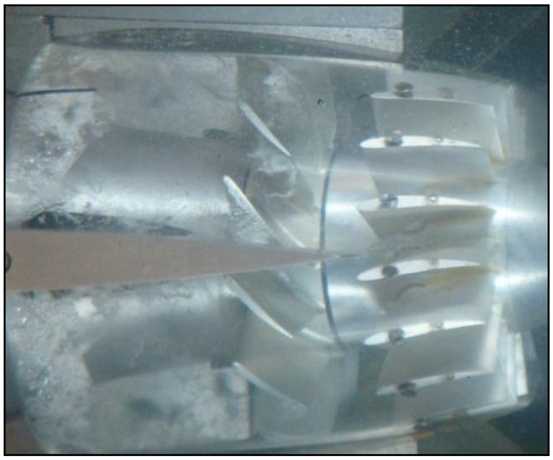

Figure 6: Rotor and Cowl Cavitation at Off Design Condition

5.2.1.Rotor Cavitation

Tests are conducted at constant RPS and different advance coefficients by varying tunnel speeds. Sheet cavitation is the first form of cavitation noticed on the rotor at all the advance coefficients. Cavitation was observed on the suction side, leading edge near the tip region, when rotor approaching to control surfaces, on further reduction in pressure sheet cavitation is growing along the chord length and observed at all the rotor positions. Tip vortex cavitation, Bubble cavitation and cavitation on pressure side of the rotor was not observed at all the test conditions. Cavitation inception pressure recorded was non-dimensionalised to obtain propeller cavitation inception number. Sheet cavitation on suction side is due to large positive angles of attack and dominant wake at control surfaces. Sheet cavitation does not depend on the viscous effects and Reynolds number, hence no corrections were applied for model scale results and the cavitation inception number measured on the rotor at control surfaces position and at in between control surfaces position was plotted against the advance coefficient. The inception numbers computed at design advance ratio was used to predict the cavitation inception speeds of the underwater vehicle at different operating depths. Cavitation diagrams only are presented in the paper and no data regarding inception speeds are presented.

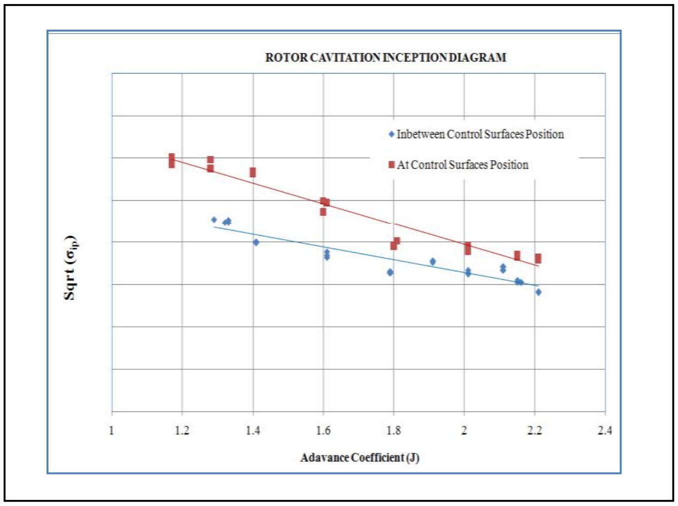

Figure 7: Rotor Cavitation Diagram

5.2.2. Stator Cavitation

Cavitation inception on the stator was recorded at 6 m/s and 7 m/s tunnel speed and at different rotor RPS to know the cavitation pattern on the stator and influence of the rotor loading and effect of Rn. Sheet cavitation on pressure side was observed near the root region at all the tested conditions and inception pressure recorded was same at all rotor RPS and tunnel speed. Influence of the rotor loading with RPS was not much significant on cavitation performance of the stator as expected. Cavitation inception numbers computed for 6 m/s and 7 m/s tunnel speed were same at all the advance coefficients, as the sheet cavitation only was observed and it is due to potential flow and does not depend on viscous effects and Reynolds number. The average inception number was considered and computed the inception depths for different underwater vehicle operating speeds.

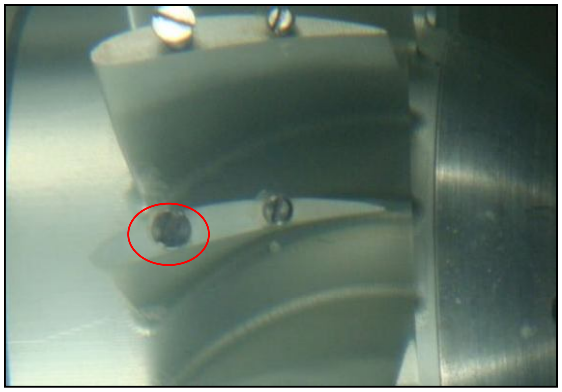

Figure 8: Cavitation on Stator

5.2.3.Cowl Cavitation

Cowl cavitation tests were conducted at 6 m/s and 7 m/s tunnel speed and at different advance ratios by varying rotor RPS to record the cavitation inception pressure and subsequently estimate the cavitation inception numbers. Inception numbers computed at different test conditions were plotted between advance coefficient and square root of Cavitation inception number (σ_i). From the results it is observed that with the increase in loading on the rotor by increasing rotor RPS, the cowl tend to cavitate early because of the increase in suction, resulting into a higher velocity and low pressure. Cavitation on the cowl was observed at the leading edge inner side at all the test conditions and the plot looks like a left branch of open propeller. Cavitation inception number recorded at design advance ratio was considered to predict the inception depths for different operating speeds without applying any Reynolds number corrections as the cavitation observed was sheet type.

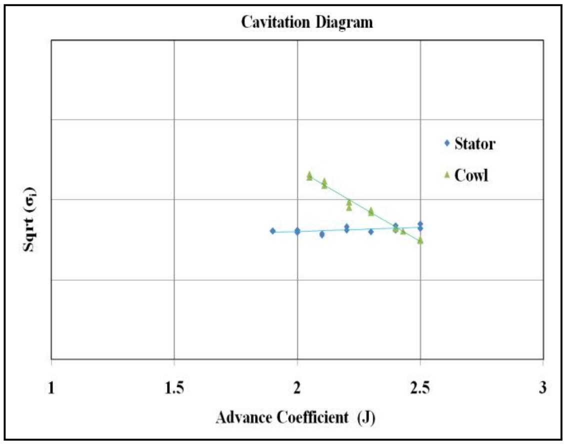

Figure 9: Cavitation Diagram of Stator and Cowl

6.Conclusion

- Based on the outcome of the model tests results, the following conclusions are drawn on the cavitation performance and torque balance of the Pumpjet:-
- Toque imbalance between rotor and stator was measured as 19-22% and it was corrected experimentally by varying stator pitch angle with detachable blades.
- This innovative idea of changing pitch angles with angular slotted rings and detachable blades resulted in to more cost effective and time saving rather than manufacturing number of stator with different pitch angles.
- Cavitation inception of the Pumpjet is determined by the sheet cavitation on the rotor at suction side leading edge and it is due to large positive attack angles.

- Cavitation on the stator is observed on pressure side, near root region and it is independent on rotor loading.
- Cavitation on cowl is observed at leading edge, inner side of the cowl and it is increasing with the rotor loading.

7.Acknowledgement

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- **Nomenclature**

D = Propeller diameter, (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)
V = Tunnel flow speed, (m/s)
R_n = Propeller Reynolds number
σ_i = Cavitation inception number
σ_{ip} = Propeller cavitation inception number
RPS = Rotations Per Second
ρ = Density of tunnel water, (kg /m³)
Kq = Torque Coefficient
Q = Torque, Nm

8.Reference

1. [Vosper P.L., and Brown A.J.] 'Pumpjet Propulsion - A British Splendid Achievement'. J. Naval Engineering, 36(2), 1996.
2. [Das H.N., Jayakumar, P., and Saji V.F.] 'CFD Examination of Interaction of Flow on High Speed Submerged Body with Pumpjet Propulsor', 5th Int. Conference on High Performance Marine Vehicles, 8-10 November 2006, Australia.
3. [Stefan Ivanell] 'Hydrodynamic Simulation of a Torpedo with Pumpjet Propulsion System', Master's thesis, Royal Institute of Technology, Stockholm 2001.
4. [KSRI] 'Test Procedure Manual', Course Material for NSTL, St. Petersburg, 2001.
5. [KSRI] Technical Reports and Documents for the Cavitation Tunnel, St. Petersburg, 2001.
6. [Suryanarayana, Ch., Roy, S.P., and Sateesh Kumar, M.] 'Hydrodynamic Performance Evaluation of an Underwater Body by Model Testing in Cavitation Tunnel', International Conference in Marine Hydrodynamics 2006, NSTL, Visakhapatnam..
7. Suryanarayana, Ch., Satyanarayana, B., Ramji, K. and Saiju, A., Experimental Evaluation of Pumpjet Propulsor for an Axisymmetric Body in Wind Tunnel. Inter J Nav Archit Oc Engng,2(1), pp.24-33, 2010
8. [Suryanarayana, Ch., Satyanarayana, B., Ramji, K. and M Nageswara Rao], cavitation studies on Axi-Symmetric underwater body with Pumpjet propulsor in cavitation tunnel,. Inter J Nav Archit Oc Engng,(2010) 2:185-194.
9. [Suryanarayana, Ch., Satyanarayana, B., Ramji, K. and M Nageswara Rao], Evaluation of cavitation performance of an axi-symmetric body with Pumpjet propulsor in cavitation tunnel,. Trans RINA, Vol 152,part A3,Intel J Maritime Engg. Jul-Sept 2010.