J Indian Inst. Sci.,65 (A), Jan. 1984, pp. 11 - 20

Observations of tip vortex cavitation inception from a model marine propeller

R.K. LODHA AND V.H. ARAKERI
Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012.

Received on July 18, 1983.

Abstract

Cavitation inception characteristics of a model marine propellar having three blades, developed area ratio of 0.34 and at three different pitch to diameter ratios of 0.62, 0.83 and 1.0 are reported. The dominant type of cavitation observed at inception was the tip vortex type. The measured magnitude of inception index are found to agree well with a proposed correlation due to Strasberg. Performance calculations of the propeller based on combined vortex and blade element theory are also presented.

Key words: Marine propeller, cavitation inception, combined vortex, blade element theory, underwater propulsion.

1. Introduction

Screw propeller is still the most commonly used device for underwater propulsion. With the advent of larger and faster ships, the probability of marine propellers operating under cavitating conditions has increased substantially. Cavitation is normally to be avoided for it can result in the following adverse effects:

(i) reduction in efficiency,

(ii) potential damage to the solid surfaces,

(iii) presence of unsteady forces resulting in severe vibrations, and

(iv) radiation of intense noise.

The first two have received significant attention in the past; however, the latter two are now receiving increasing attention (see for example Van Manen[1] and Baiter[2]). On a marine propeller there are several potential low pressure regions which can be prone to cavitation. Thus, as pointed out by Cumming and Morgan[3], depending upon its location, several types of cavitation, are observed on a marine propeller, namely:

(i) tip vortex

(ii) hub vortex

(iii) leading edge attached sheet
  — suction side
  — pressure side

(iv) midchord bubble and

(v) cloud

The possible occurrence of leading edge attached sheet and midchord bubble type can be predicted to a certain extent at the design stage itself. However, the prediction of the onset of tip and hub vortex cavitation is significantly more difficult if not impossible. The latter two are associated with the vortex system of the propeller whereas the former two with the detailed pressure distribution characteristics of the sectional blade elements of each propeller blade. Presently, we are concerned with the onset of tip vortex cavitation and hence we will elaborate further only on this type.

In order to understand the vortex system of a propeller it is helpful to consider each blade as being made of airfoil-shaped sectional blade elements. Each element is subject to an elemental lift and drag force which add up to the total generated thrust and absorbed torque by the propeller. Thus, a propeller blade is a finite lifting wing and as is well known in airfoil theory such a wing can produce a tip vortex system. Since a propeller is both rotating and translating the tip vortex takes on a helical shape (see fig. 7). The strength of the tip vortex is primarily dependent on the lift distribution in the spanwise direction. Therefore, unloading of the blade near the tip area can be helpful in reducing the strength of the tip vortex. However, a propeller blade, unlike a wing, generates most of its lift in the tip area since the velocities are higher there in view of the larger radius. Hence, a compromise has to be reached at the design stages.

Generally the onset of tip vortex cavitation is not considered to be dangerous since it does not result in the first three adverse effects due to cavitation noted earlier. The fourth effect normally is not of significance for civilian applications but can be crucial for miltary applications. As an example of the latter, in one instance reported by Strasberg[4], it was found that the level of radiated noise from a submarine propeller increased substantially at speeds of the order of 4 knots. The designers of the propeller insisted that no cavitation should be possible at such low speeds. Of course, they were considering only blade cavitation and eventually the increase in the radiated noise was traced to the onset of tip vortex cavitation. This was later confirmed from model studies. Therefore, if the level of radiated noise is a criterion for propeller performance then the possible onset of tip vortex cavitation has to be considered at the design stage itself. The present state-of-art permits this to be done only through model studies.

A water tunnel facility is almost always used for conducting model propeller studies. In some cases the propeller is placed in a uniform flow to give its open water characteristics and in other cases the back portion of the hull including strut system is stimulated in front of the propeller to give propeller characteristics in the presence of a simulated wake of the actual ship. Of course, due to Reynolds number differences, the simulation is not perfect. In any case the model studies should include the observation of the incipient cavitation index $(\sigma_A)_i$ *vs* the advance coefficient J and the measurement of thrust coefficient C_T *vs* J.

The non-dimensional parameters σ_A, C_T and J are defined* as:

$$\sigma_A = \frac{P_\infty - P_V}{1/2\ \rho V^2} \tag{1}$$

$$C_T = \frac{T}{\rho n^2 D^4} \quad \text{and} \tag{2}$$

$$J = \frac{V}{nD} \tag{3}$$

The magnitude of σ_A at just the beginning conditions of cavitation is designated the incipient cavitation index denoted by $(\sigma_A)_i$. The exact method of extrapolating model test results to prototype conditions is a complex and controversial matter and we only refer to the discussion of Berg and Kuiper[5] and Noordzij[6] on this subject.

In the present work, we have tried to study the effect of variation of pitch to diameter ratio of a model propeller, otherwise identical on the onset of tip vortex cavitation. First the performance computations of the propeller are presented and this is followed by the results of the observations of tip vortex cavitation.

2. Background on the development of propeller theory

The development of propeller theory has been essentially on three independent lines, namely:

(i) momentum theory,

(ii) blade element theory, and

(iii) vortex theory.

The momentum theory initiated by W.J.M. Froude in 1865 and further developed by R.E. Froude, still forms a sound basis for estimating the ideal efficiency of a properller, giving the upper limit of performance of a properller. The defect of the momentum theory is that it gives no information on the detailed design aspects of the propeller.

The blade element theory initiated by W. Froude in 1878 was mainly developed by S. Drzewiecki. The basis of analysis is that the propeller blade is divided into a large number of elements along the radius and that each of these is regarded as an airfoil moving at a constant axial velocity and the rotational speed which varies from element to element along the blade radius. Thus, the angle of attack experienced by the airfoil section is simply given by the difference of the local propeller pitch angle and the angle of the resultant velocity W having V and $\gamma\Omega$ as components. From knowing the lift and drag characteristics of the airfoil corresponding to this angle of attack the sectional thrust and torque can be calculated. The overall thrust and torque are then determined by summing the sectional thrust and torque contributions.

* see also nomenclature

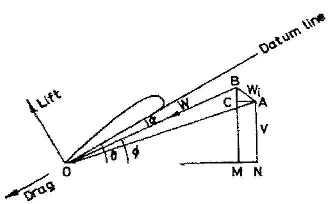
The vortex theory initiated by Betz in 1919 has been comprehensively developed by Goldstein[7]. This theory is based on the concept that trailing vortices spring from the rotating blades of the propeller and form a slipstream consisting of helical vortex sheets. The interference velocity experienced by the blades must be calculated as the induced velocity of this vortex system, and the hydrodynamic reaction on any blade element is derived from this modified system of velocities (and not V and $\gamma\Omega$ as used in blade element theory) in association with airfoil characteristics corresponding to two-dimensional motion. The calculation of these induced velocities is very complex and hence the analysis is based on the assumption that the propeller has large number of blades. Thus the velocity around any annulus of the propeller disc remains uniform and the vortex theory becomes identical to the blade element theory, including the interference velocities as determined by the general momentum theory and using airfoil characteristics corresponding to two-dimensional motion. The vortex theory, being the most comprehensive of the three methods considered and at the same time being considerably simpler than some of the modern propeller theories based on lifting surface considerations, was used for the present computations.

3. Computational procedure

The computational procedure using the vortex theory has been clearly outlined by Glauret[8] It primarily involves the determination of the axial and rotational interference factors indicated in fig. 1. as a function of the radial location.

The elemental forces at the local radial location are then determined using these interefer-ence factors, geometry of the propeller blades and the lift and drag characteristics of the blade element. The selection of the exact number of blade elements required for these calculations mainly depends on the desired accuracy. However, experience (see for example Hill[9]) has shown that four to five blade elements distributed at different radii give reasonably accurate results. Hence, in the present calculations, five elements were selected at locations of 30, 50, 70, 80 and 90 per cent of the propeller radius.

The two-dimensional lift coefficient, C_L of the local blade section, was computed as a function of α using a computer programme based on the method due to Martensen[10]. The accurate estimation of the drag coefficient is of little importance; in fact, in one published design method[9] a standard value of $C_D = 0.008$ was used. The present calculations are also based on a constant value for $C_D = 0.008$. It may be noted here that even if the C_D term is completely neglected the error introduced in the estimation of the efficiency is less than 2 per cent.



AN = Axial velocity, V
ON = Rotational velocity, Ωr
AB = Induced velocity, W_i
OB = Effective relative velocity of blade, W
BC = Axial interference factor, a
AC = Radial interference factor, a'

FIG 1. Velocity and force diagram of a marine propeller blade element.

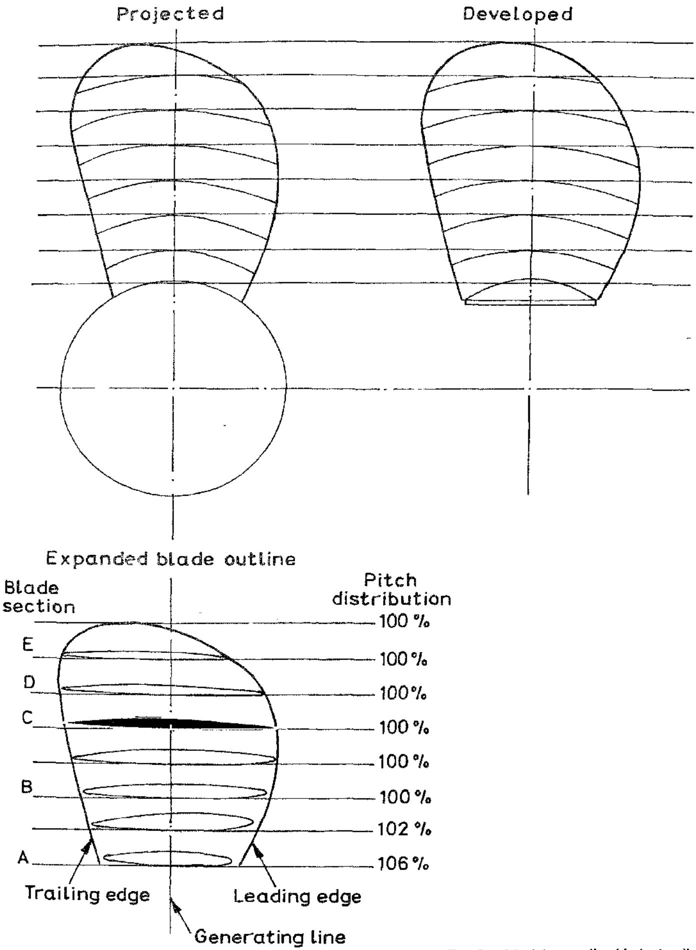


FIG. 2. Model propeller blade details.

4. Computational results

The method just outlined was used to calculate the hydrodynamic performance of a three-bladed marine propeller (fig. 2), having a diameter of 183.2 mm, developed area ratio of 0.34 and pitch to diameter ratios of 0.62, 0.83 and 1.0. The hydrodynamic performance characteristics of the model propeller at three different P/D ratios are shown in fig. 3. As expected, the peak in efficiency shifts to a larger value of J as P/D ratio is increased and also the peak efficiency increases as P/D ratio increases. Similar observations have also been made by Troost[11] on a three-bladed propeller of the Troost B-3 series having similar geometrical characteristics as ours. One such comparison along with experimental measurements of Arakeri *et al*[12] is shown in fig. 4. It is to be noted that the three results agree well giving us confidence in the present computation which is based on certain approximations like the assumptions of constant C_D, infinite number of blades, infinitesimal contraction of the slip stream, etc. Under these assumptions, the vortex theory as used simply becomes the combination of blade element theory and the ideal momentum theory which is used to calculate the interference factors a and a^1. In view of this, the efficiencies predicted presently would be expected to be close to those predicted on the basis of ideal theory. In fact, this is found to be the case, in the sense that the presently computed efficiencies are close to 90% of the ideal efficiencies*.

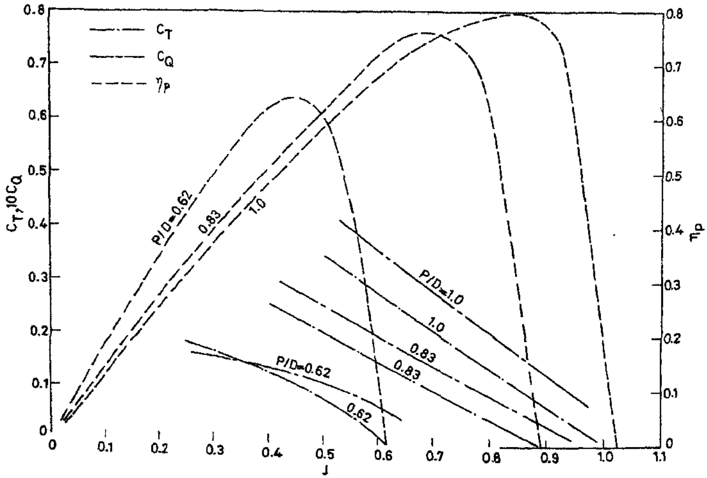


FIG 3. Performance characteristics of the marine propeller.

*The authors are grateful to one of the referees who pointed this out.

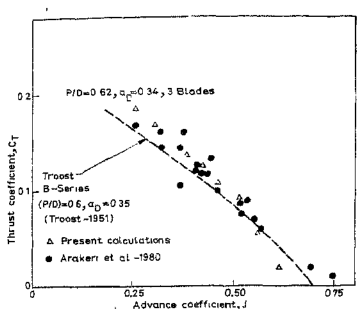


FIG 4 Comparison of computed thrust coefficient.

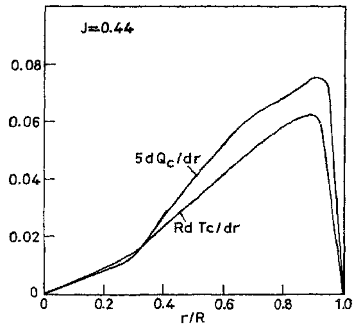


FIG 5 Thrust and torque grading curves $P/D = 0.83$

In reality, however, the efficiencies are expected to be much lower being generally of the order of 70% of the ideal efficiencies. Therefore, there is no doubt that the present theory has some shortcomings, but it still provides very useful information on the sectional loading characteristics which can be used to infer the susceptibility of the propeller to tip vortex cavitation on-set.

One example of the sectional loading characteristics of the present propeller along the spanwise direction is shown in fig. 5. It is clear that the loading keeps on increasing almost to the tip and hence the strength of the tip vortex is likely to be strong. As it will be indicated later, this, in fact, is to be true since the dominant type of cavitation observed at inception was the tip vortex type (fig. 7).

5. Experimental methods

Cavitation inception observations on a model propeller of 183.2 mm in diameter were made in the Indian Institute of Science high speed water tunnel facility. This is a closed loop facility with a circular test section having a diameter of 381 mm. It is not uncommon to test model propellers having diameters as large as one half of the test section diameter as done presently. The velocity and the static pressure in the test section can be varied independently. This feature is essential for cavitation testing. Recently the facility has been adapted for model propeller testing and the details are given in Arakeri *et al*[12]. The inception tests were carried out by holding the tunnel velocity V and rotational speed of the shaft, n constant and then the static pressure was lowered slowly until signs of cavitation were detected under the illumination of stroboscopic lighting synchronized with the shaft rotational speed. This was repeated for different values of V with n fixed at about 2300 rpm thus giving a range of J values. The static pressure in the test section and the pressure drop across the contraction cone needed to compute the velocity V were measured with the help of mercury U-tube manometers. The air

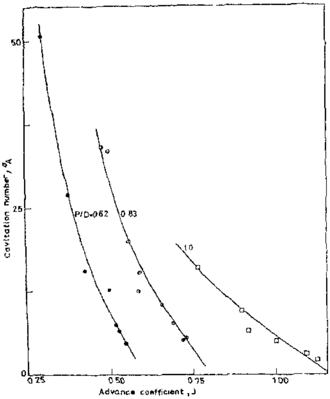


FIG 6. Tip vortex cavitation inception characteristics of the model marine propeller.

FIG 7. Developed tip vortex and sheet cavitation on the model propeller ($P/D = 0.83$).

content of the water was monitored with the help of an oxygen analyzer. This parameter was varied from about 55 to 75 per cent of saturation at atmospheric conditions; however, no significant differences were observed in the magnitude of incipient cavitation index. Nominal water temperature for the present tests was 25°C.

6. Results and discussion

Cavitation inception characteristics of the present model propeller at different values of advance coefficient for pitch settings of 0.62, 0.83 and 1.0 are shown in fig. 6. As noted earlier, the cavitation at inception was of the tip vortex type and a photograph of such cavitation at an advanced stage is shown in fig. 7. It is clear from the results shown in fig. 6 that at a fixed value of J the incipient cavitation index has a higher value as P/D ratio is increased. This is to be expected since as shown in fig. 3 at fixed value of J the loading increases with an increase in P/D ratio. Therefore, we find that $(\sigma_A)_i$ is a function of both J and P/D and to overcome this difficulty Strasberg[4] has suggested a correlation of $(\sigma_A)_i$ with slip of the propeller S, given by

$$S = 1 - J/(P/D)_{0.7r} \tag{4}$$

The exact correlation suggested by Strasberg based on model submarine propellers is

$$(\sigma_A)_i = 1.9\, e^{6.6S} \tag{5}$$

and a comparison of present data with the above correlation is shown in fig. 8. The agreement can be considered to be quite satisfactory, in particular, at P/D values of 0.62 and 0.83.

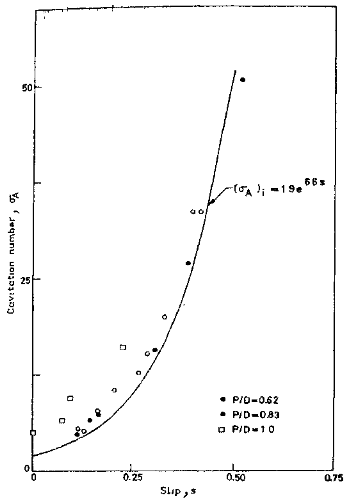


FIG 8 Comparison of present inception data with a correlation due to Strasberg.

7. Concluding remarks

Marine propellers loaded quite heavily till almost the blade tip tend to generate tip vortex cavitation much earlier than the onset of other types of cavitation. This has been confirmed on a model propeller based on computations in combination with experimental observations. Therefore, if the level noise radiation is a crucial aspect of a marine propeller application then the above fact should be considered at the design stage itself.

Acknowledgements

The financial support for the study was in part by the Electronics Commission and in part by the Ministry of Defence through DNRD. This support is gratefully acknowledged. The authors would also like to thank Prof. S. Soundranayagam for discussions and Mr. A. Suryanarayanan and Mr. K. Mani for their assistance in the computational and experimental work respectively.

Nomenclature

a	axial interference factor	C_Q	torque coefficient, $Q/\rho n^2 D^5$
a'	rotational interference factor	C_T	thrust coefficient, $T/\rho n^2 D^4$
C_D	drag coefficient	D	diameter of propeller
C_L	lift coefficient	J	advance coefficient, V/nD

n rotational speed in rps

P pitch of the propeller

P_v vapour pressure of water

P_∞ reference static pressure

Q torque absorbed by the propeller

r radial distance

S slip of the propeller (eqn. 22)

T thrust generated by the propeller

V advance or axial velocity

W effective relative velocity of blade

W_t total induced velocity

α angle of incidence

η_p propulsive efficiency of the propeller, $VT/\Omega Q$

Ω angular velocity

ϕ angle of inclination of W to the plane of rotation

ρ density of water

σ_A cavitation number $(p_\infty - p_v)/1/2\rho V^2$

$(\sigma_A)_i$ cavitation number at inception

θ blade angle, usually reckoned from plane of rotation

References

1. Manan J.D. Van — The effect of cavitation on the interaction between propeller and ship's hull, *Int. Shipbldg. Prog.* 1972, **19**, 3.
2. Baiter, H.J. — Aspects of cavitation noise, Netherlands Ship Model Basin, *Publ No. 490*, 1974.
3. Cumming, R.A. and Morgan, Wm.B — Propeller design aspects of large, high-speed ships, Netherlands Ship Model Basin, Publ No 490, 1974.
4. Strasberg, M — Propeller cavitation noise after 35 years of study, Proc. ASME Symp. "Noise and Fluids Engineering" 89, 1977
5. Berg W Van den, and Kuiper, G — Experience after one year of tests in the NSMB depressurized towing tank, Netherlands Ship Model Basin, Publ No 490, 1974
6. Noordzij, L — A note on the scaling of tip vortex cavitation inception, *Int. Shipbldg. Prog, 1977,* **24.**
7. Goldstein, S — On the vortex theory of screw propellers, *Proc. Royal Soc Ser. 1929,* **A 63.**
8. Glauert, H — *Aerodynamic theory*, Vol. IV (Ed Durand), Chapter I, 1935.
9. Hill, J.G — The design of propellers, *Trans. SNAME,* 1949, **57.**
10. Manitensen, E — Die berchnung der druckverteilung an dicken gitterprofilen mit Hilfe von Fred holmschen integral-gleichungen Zweiter Art, Max Plank Institut, Mitteilungen Nr. 23 (English translation), 1959.
11. Troost, L. — Open-water tests with modern propeller forms, *Trans. NECIES,* 1951, **67.**
12. Arakeri, V.H, Mani, K, and Munjal, M.L. — Cavitation and noise studies on a model propeller: final report, Rept. No. STL-DS/TR-80.3 Division of Mechanical Sciences, Indian Institute of Science, Bangalore 560 012, India, 1980