Marine propeller performance: Computational prediction and experimental validation

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Abstract

An outline of the recent developments behind THPUF-3A computer program, based on MIT/UTA publications and its user-friendly implementation at EPMB are given. The present work is dedicated to the validation of this propeller performance code by comparison with model test data of EPMB for sheet cavity extents on the blades and steady forces for several propellers in open water and behind ship conditions, as well as the hull pressure fluctuations due to propeller cavitation. The very promising results obtained permit to conclude that THPUF-3A is a powerful tool for marine propeller design purposes.

1 Introduction

The computer-aided marine propeller performance prediction is of permanent interest and development in naval engineering. The experimental validation is a necessary task to be done after the development of the codes, clarifying the applicability of the methods and guiding their further improvement. El Pardo Model Basin (EPMB), as a member of an International University/Navy/Industry consortium on propeller performance (UNICPP) wishes to contribute to this goal, showing the results of its work on implementing the programs developed in Massachusetts Institute of Technology (MIT) and the University of Texas at Austin (UTA). The new version of the propeller performance/hull pressure fluctuations codes THPUF-3A/HULLFPP has been installed and an user-friendly environment prepared at EPMB. Series of calculations for propeller models at different regimes, previously tested in the towing tank and cavitation tunnel, have been performed and compared. The next section uses some explanatory figures taken from the publications referenced.
2 Outline of the method and the computer programs

2.1 The method

Various publications describe the method and the algorithms for propeller performance computation that will be summarised below to clarify the hydrodynamic background used. The basic well known (Kerwin & Lee and Lee) numerical lifting-surface technique for cavitating propellers, called VLM (vortex lattice method) is used. Several improvements have been introduced in the frames of the UNICPP, aimed to obtain a better prediction code:

- The linearized effect of thickness on loading was introduced as in Kinnas.
- The trailing vortex wake consists of transition region with contraction and deformation and ultimate region composed of Z (number of blades) concentrated helical tip vortices and a single hub vortex. In the wake alignment procedure adopted from Greeley & Kerwin the transition wake geometry is approximately adjusted to the resulting flow in an iterative way, although the radius of the ultimate wake and the length of the transition zone are based on observations (0.83 and 1.5 of propeller radius, respectively).
- In case of inclination of the propeller, typical for high-speed ships, the key blade at each angle encounters different wake geometry. The approximation adopted (Kinnas & Pyo) decomposes the inflow to axial and vertical components and uses only the induced velocity due to the axial inflow for the still complicated and time consuming alignment procedure. The effect of the inclined wake on cavity shape is shown as an example in Figure 1.
- The effect of the hub has been included by imaging technique (Kinnas & Coney). Its influence may be important, as shown in the example of Figure 2.
- The linear theory tends to overpredict the extent of cavities and wrongly predicts larger cavities as the thickness increases. A leading edge (L.E.) correction has been introduced by Kinnas and implemented in the code. The effect is significant, reducing over the linear theory the extent and volume of the cavities. Figure 3 shows an example of this, for a 2-D cavity solution.
- A leading-edge type correction for the tip vortex has been introduced by Kinnas et al. Its effect on the cavity volume may be appreciable, as shown in the example of Figure 4.

![Figure 1: Cavity shape for shaft inclination of 20 degrees.](image)

![Figure 2: Effect of hub on cavity shape](image)
With L.E. correction

Pure linear theory

Figure 3: Cavity extent with and w/out leading edge correction.

Figure 4: Effect of tip flow angularity.

The code assumes detachment of the cavity at the leading of the blade, as is usually, but not always the case. Recent developments, not yet validated, include midchord cavity detachment and possibility to calculate supercavitating propellers. The pressure fluctuations induced on the hull by a cavitating propeller are calculated by solving the diffraction potential on the hull (Breslin et al. 3).

2.2 The computer programs

The computational environment is a DEC 3000 Alpha station of 144 Mhz and VMS operating system. The geometric and ship wake velocity (in case of behind ship conditions) data are introduced by screens or taken from the EPMB data base and converted to the format required for THPUF-3A (Kinnas et al. 4) by the EPMB user-friendly pre-processor program PREPUF. The user has various options to choose parameters that affect the solution. The MIT HULLFPP program calculates the pressure fluctuations on the hull. The output files created are used by various postprocessor programs of MIT and the EPMB post-processing program POSPUF to generate the numerical and graphic output:

- geometric, wake velocity, regime and control parameters data about the calculated case;
- steady forces on one blade and the whole propeller - open water curves;
- cavity extent and volume at several angular positions of a blade;
- amplitudes and phases of unsteady forces and moments on the blades and the propeller shaft for the cavitating and non-cavitating propeller;
- cavity volume velocity harmonics;
- pressure distribution on both sides of a blade at several angular positions;
- pressure fluctuations harmonics on the control points of the hull.

A full unsteady case of propeller performance for a grid 20x18 is calculated in 12 minutes for horizontal and about 20 minutes for inclined shaft. The computer time for the fluctuating pressures on the hull is about 10 minutes.
3 Validation of THPUF-3A

The validation of the code has to be performed comparing results of the calculations with experimental data from tests with physical models. EPMB has undertaken this job using for this purpose results of tests carried out in its laboratories (mainly a towing tank of 320x12.5x6.5 m. and a cavitation tunnel of 0.9x0.9 m. measuring section).

For this study several propellers of EPMB stock were chosen (Table 1). They have quite different geometries concerning number of blades (Z), pitch ratio (H/D) and camber distributions, blade-area ratio (A_E/A_0), skew and rake, type of sections, etc. This heterogeneity was deliberately selected to explore the behaviour of the code faced to very different cases and philosophy of design. All the propellers correspond to real designs of ships as different as tankers, containerships, patrol-boats, oceanographic vessels, etc.

<table>
<thead>
<tr>
<th>Prop. No.</th>
<th>Z</th>
<th>(H/D)_0.7</th>
<th>Skew max. (°)</th>
<th>A_E/A_0</th>
<th>Type of sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>2399</td>
<td>4</td>
<td>0.765</td>
<td>10.6</td>
<td>0.60</td>
<td>Wageningen</td>
</tr>
<tr>
<td>1687</td>
<td>5</td>
<td>0.924</td>
<td>10.5</td>
<td>0.75</td>
<td>Wageningen</td>
</tr>
<tr>
<td>2431</td>
<td>5</td>
<td>0.929</td>
<td>22.4</td>
<td>0.80</td>
<td>NACA 16</td>
</tr>
<tr>
<td>2378</td>
<td>5</td>
<td>0.775</td>
<td>50.0</td>
<td>0.77</td>
<td>NACA 66</td>
</tr>
<tr>
<td>2429</td>
<td>5</td>
<td>0.960</td>
<td>19.4</td>
<td>0.78</td>
<td>NACA 66</td>
</tr>
<tr>
<td>2267</td>
<td>3</td>
<td>1.181</td>
<td>12.5</td>
<td>0.88</td>
<td>NACA 66</td>
</tr>
</tbody>
</table>

Table 1. Main geometrical particulars of studied propellers

The validation work has been carried out in four stages: open water, behind ship model condition, cavitation extension and hull pressure fluctuations due to propeller cavitation. Results of the validation are presented below.

**Open water.** Comparative results of K_T, K_Q and \( \eta_0 \) for a range of J are presented in Figures 5 and 6. Agreement is quite satisfactory, mainly for the design J, which is about the mid point of the J range shown in the figures, for each propeller. Nevertheless, it can be observed a certain tendency in THPUF-3A to underestimate forces at low J and to overestimate efficiency (ETA0) at high J. This behaviour is of minor importance in the design process, because the majority of ship propellers will always work in a zone of J near its design point. However, for special cases like trawlers or tugs, whose propellers can be often working at low J, away from the design point, the forces in these situations will be underestimated. This point will need special attention to be solved in future versions of the program.

**Behind ship model condition.** Mean steady thrust and torque of each propeller working behind its corresponding models were measured and calculated. Wake survey tests of different ship models were made beforehand.
Fig. 5. Propeller open water characteristics
Fig. 6. Propeller open water characteristics
Results are presented in Table 2 for all the propellers except no. 2267 for which no reliable self-propulsion tests were available. Calculations have been made converting the nominal wake field to effective wake by means of a proportional method (Van Manen\textsuperscript{10}). This method, although very rough and simple, have been used because no other reliable method for non-axisymmetric wakes was available at the moment at EPMB.

<table>
<thead>
<tr>
<th>Propeller no.</th>
<th>$\Delta T$ (%)</th>
<th>$\Delta Q$ (%)</th>
<th>$\Delta \eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2399</td>
<td>+0.2</td>
<td>-1.1</td>
<td>-1.7</td>
</tr>
<tr>
<td>1687</td>
<td>+0.3</td>
<td>-0.1</td>
<td>+0.4</td>
</tr>
<tr>
<td>2431</td>
<td>-2.6</td>
<td>-1.2</td>
<td>-1.4</td>
</tr>
<tr>
<td>2378</td>
<td>-4.0</td>
<td>-3.8</td>
<td>+0.2</td>
</tr>
<tr>
<td>2429</td>
<td>+1.3</td>
<td>+2.4</td>
<td>-0.8</td>
</tr>
<tr>
<td>Mean absolute</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>value of errors</td>
<td>1.7%</td>
<td>1.7%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

Table 2. Results of self-propulsion tests and calculations

Results of Table 2 are differences in percentage between calculations and experiments. Despite of the simplifications of the method, the results are very good, showing differences lesser than 4% for all the propellers. Specially the prediction of the propeller efficiency is excellent.

**Cavitation patterns.** Observations of cavitation extension (mainly of the “sheet” type) were made in the Cavitation Tunnel for each propeller with its corresponding simulated wakes. Calculations for every propeller were carried out, at the same cavitation number ($\sigma$) that in the tests. Comparative results can be seen in Figures 7 and 8. The prediction can be judged as very satisfactory and only minor differences arise. Of special interest are the results of propeller 2267 (high-speed patrol-boat) with very wide blades and a shaft inclination of 7.4°, while the rest had horizontal shafts. Inclination angle was taken into account in the calculations and it can be observed that the asymmetry between port and starboard of the large cavitating areas is correctly predicted.

**Hull pressure fluctuations due to propeller cavitation.** These tests were carried out only with propeller 1687. Pressure measurements were made inside the Cavitation Tunnel in four points on the hull surface. Point A is just on top the propeller. Points B and C are on the centreline plane, 0.17 D(propeller diameter) fore and aft of point A. Point D is in the port side, 0.17 D from point A. Results are presented in Table 3. As can be seen from the table, the agreement is quite satisfactory. Not only tendencies of pressure gradients are correctly predicted, but also numerical values are reasonably close to the experimental ones.
Propeller no. 2399 - $\sigma = 2.46$

Propeller no. 1687 - $\sigma = 1.59$

Propeller no. 2431 - $\sigma = 2.32$

Fig. 7. Cavitation patterns
Table 3. Hull pressure fluctuations. Amplitude of 1st blade harmonic.

<table>
<thead>
<tr>
<th>Point</th>
<th>$A_{1\text{calc}}$ (kPa)</th>
<th>$A_{1\text{exp}}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (top)</td>
<td>2.05</td>
<td>2.01</td>
</tr>
<tr>
<td>B (centre-fore)</td>
<td>3.94</td>
<td>3.10</td>
</tr>
<tr>
<td>C (centre-aft)</td>
<td>1.95</td>
<td>1.71</td>
</tr>
<tr>
<td>D (port)</td>
<td>1.12</td>
<td>1.35</td>
</tr>
</tbody>
</table>

4 Conclusions

A wide validation of the code THPUF-3 A has been made, by comparison of calculations with experimental results carried out at El Pardo Model Basin.
In general, very satisfactory results have been obtained, and it can be concluded that THPUF-3A method and code are a very powerful and valid tool for conventional propeller design purposes.

5 Acknowledgements

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References