PERFORMANCE OF A FAMILY OF SURFACE PIERCING PROPELLERS

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SUMMARY: Experimental tests have been performed on a systematic series of surface piercing propellers with varied number of blades (4 and 5) and pitch ratio (from 0.8 to 1.4). Influence of depth of immersion and shaft inclination is discussed and results for variations in these parameters are presented. Regression equations are given describing the relationship of the thrust and torque coefficients for advance coefficients above the critical values. Influence on Weber number is briefly considered, confirming results of previous works. This work is the result of a research on the performances of surface piercing propellers undertaken by the University of Genoa and was partly developed as a doctoral thesis.

1. INTRODUCTION

Surface piercing propellers application for leisure boats has constantly grown in past years, with an increasing number of boats adopting it, especially in the high-speed segment of the market. Nevertheless, a considerable lack of studies and available data on this specific propeller type still exists, and its behaviour is still far to be completely investigated, due to its relatively recent introduction, the limited (but increasing) range of applications and the fact that data are in many cases considered as protected know-how for industrial or military reasons.

Numerical methodologies, whose application is widespread for conventional propellers, are still far from being applied successfully and with sufficient confidence to surface piercing propellers and their design, because of the considerable difficulties connected to the numerical modelization of this particular propeller type, which typically works at the interface between two fluids, i.e. water and air, leading to complexities not existing for the conventional case.

Despite the existence of these objective problems, designers of surface piercing propellers currently adopted have been able to obtain open water propeller efficiencies which are comparable (even if still a bit lower) to those of conventional propellers with same principal characteristics (namely pitch to diameter ratio). Moreover, surface piercing propellers allow to considerably reduce appendages resistance with respect to conventional configuration with immersed shaft axes, virtually eliminating most of it. Considering that appendages resistance for fast craft can represent 30% or more of total resistance, a considerable reduction in power requirements can be obtained by means of the adoption of this kind of propeller.

Another important characteristic which makes surface piercing propeller particularly attractive in the segment of fast crafts is the absence of cavitating phenomena (which on the contrary can be dramatically severe for immersed propellers limiting their application) due to their peculiar functioning; in particular, the presence of an air sheet on the blade prevents inception of vapour bubbles and thus cavitation.

These two main features make application of surface piercing propellers to fast crafts very attractive, despite some problems which have to be carefully analysed in their design; among them, thrust and torque fluctuations due to the typically non stationary functioning of surface piercing propellers, with blades entering and coming out violently in and from water once a revolution, can lead to structural problems on propeller itself and on all shaftline and transmission, which have to be kept in mind and monitored.

Typical installation of SPP at stern consists of shaftline coming out of transom, which leads to a propeller immersion of about 50% in “transom dry” conditions and high speed, as reported in following figure 1.

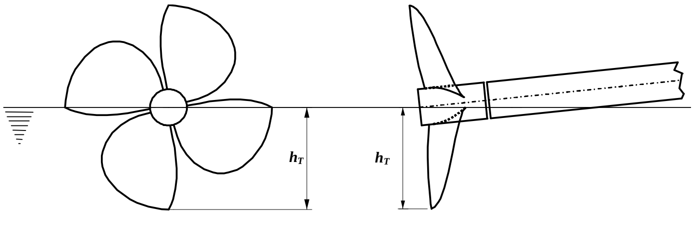

Figure 1: Typical SPP arrangement

One of the main differences between surface piercing propellers and conventional propellers are related to typical profiles utilised (figure 2) and to the blade shape which presents a peculiar skew distribution; both of them are usually studied in order to lower, as far as possible, impact into water, moreover profiles are studied in order to increase thrust produced by propeller face, since ventilated propeller back contribution is almost negligible in some operating conditions.

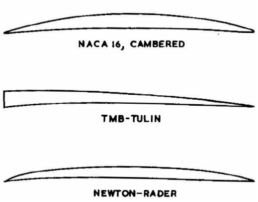

Figure 2: Possible SPP blade sections

2. MAIN PARAMETERS

Main parameters influencing SPP behaviour (in terms of usual propeller characteristic curves) are the same usually adopted for conventional propellers (namely blade number z, pitch/diameter ratio P/D, expanded blade area ratio A_E/A_O, advance coefficient J, Reynolds number *Re* and cavitation number σ), with additional parameters introduced in order to consider that propeller operates at interface between air and water (immersion coefficient I_T, Weber number *We*); moreover, some parameters which are usually considered of lower importance for conventional propellers, i.e. longitudinal and horizontal shaft angles (Ψ and γ respectively) and Froude number *Fr* play in this case a significant role,

As a consequence, thrust and torque coefficients, in case of SPP, are usually represented as follows:

$$K = f(z; P/D; A_E/A_0; J; I_T; Re; \Psi; \gamma; \sigma; Fr; We) \qquad (1)$$

Influences of different coefficients can be briefly summarized as follows:

- z, P/D and A_E/A_O have an influence similar to the one for conventional propellers
- J influence is similar to conventional propellers at values above critical J_{CR} , in correspondence to the so-called partially vented regime, corresponding to area 1 in following figure 3, while at lower values a different behaviour is experienced (fully vented regime, corresponding to areas 3, 4 and 5 in figure 3)
- Nondimensional numbers (*Re*, *Fr* and *We*) can introduce significant scale effect between results on models and in full scale if not properly taken into account; in particular Weber number is in general defined as the ratio between inertial and surface tension forces, as in the following equation 2, where V and L represent velocity and length of interest and κ is water kinematic capillarity:

$$W_n = \frac{V^2 L}{\kappa} \qquad (2)$$

  Weber number has been found to be probably the most influent coefficient for this kind of propeller, as reported in [1][2][3][4]

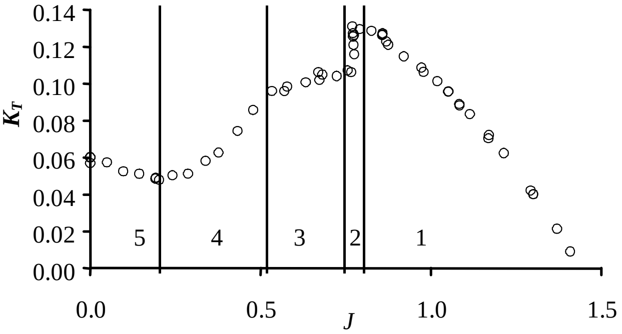

Figure 3: Typical SPP K_T vs J plot

- Shaft inclinations are much more important in this case since SPP are characterised by considerable vertical and lateral forces with respect to conventional propellers due to their asymmetric functioning conditions; in particular, horizontal forces can reach very high values (up and over to 50% longitudinal thrust) and thus have to be carefully taken into account; these additional forces are influenced by blade shape, and in particular by rake and skew;
- Regarding cavitation number, (σ), as already anticipated SPP are considerably less influenced by cavitation phenomena, which are present (if any) only in correspondence to advance coefficient values higher than J_{CR}, where blade back is still not ventilated and vapour bubbles can be crated at very low cavitation numbers.
- Immersion coefficient I_T, defined as:

$$I_T = \frac{h_T}{D} \qquad (3)$$

  where h_T and D are maximum propeller immersion and propeller diameter respectively, is a fundamental parameter for SPP; in particular, it has been observed [2][5][6] that force coefficients vary proportionally to this coefficient

It is not the scope of this work to go into a deeper detail of SPP characteristics; more information can be found in literature from previous works already mentioned. In present work, results obtained during a PhD activity for a systematic series of 5 bladed propellers [7] are presented and compared with other data previously obtained in studies carried out by DINAV and DIN on another systematic series of 4 bladed propellers [5].

3. DESCRIPTION OF MODELS AND TESTS FOR THE SYSTEMATIC SERIES

Surface piercing propellers family 5.67 consists of three 5-bladed models characterised by the same profiles previously adopted for propeller family 4.68 (4-bladed [5]). These three models are characterised by different P/D ratios, namely 0.8, 1.0 e 1.2 (it has to be noted that in the case of 4.68 series a fourth value of P/D was analysed, namely 1.4); A_E/A_0 ratio is set to 0.67 for all models (very similar to value of 0.68 adopted for 4-bladed family). All models have a diameter of 0.25 m, and are characterised by a rake angle of 6°.
This propeller family, as the previous 4.68, has been created from propellers whose design was carried out by Renato ”Sonny” Levi [8][9], and their complete geometry has never been published for industrial property reasons .

In following table 1, propellers tested are reported:

Model. No.	P/D
E9701	0.8
E9901	1.0
E9702	1.2

Table 1. Series 5.67 Models

All experimental tests on these models have been carried out at DINAV Cavitation Tunnel at Genoa University. Cavitation tunnel is characterised by a test section having 2 m length and a squared transversal section with width and height equal to 0.57 m. The Tunnel, originally built only for conventional propellers testing, has been suitably modified in order to obtain a free surface flow to test SPP [1], as represented in following figure 4.

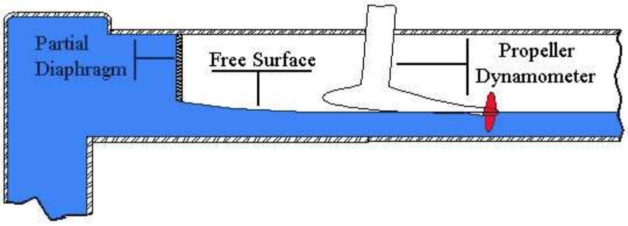

Fig. 4. Cavitation tunnel modification for SPP testing

During tests, free surface level in correspondence to propeller is about 0.25 m, and tests are typically carried out with a flow speed ranging from 2.5 and 3.5 m/s.
The 3 models have been systematically tested varying parameters I_T and Ψ; in particular, four different values of immersion coefficient around the typical 0.5 (namely I_T = 0.4, 0.5, 0.6 e 0.7) and three longitudinal shaft inclinations (namely 4°, 6° e 8°) have been tested. As a result, a total of 36 trials have been performed.

4. EXPERIMENTAL RESULTS

As an example, in following figures 5-7 experimental results in correspondence to testing conditions with various I_T values and Ψ=6° for propeller E9701 (P/D=0.8) are reported.

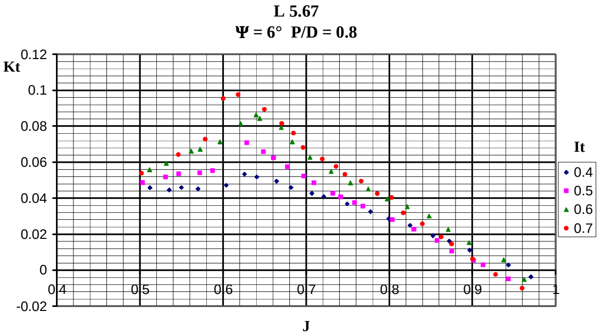

Fig. 5. Propeller 9701 - Ψ=6° - K_T curves

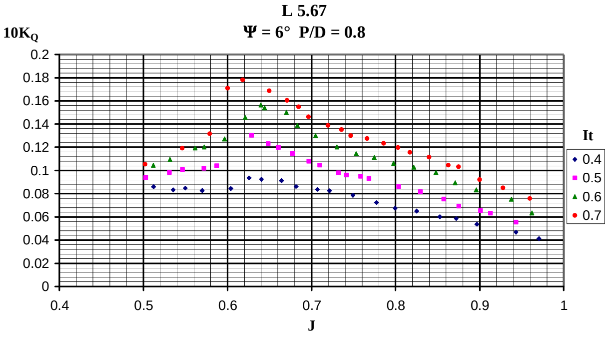

Fig. 6. Propeller 9701 - Ψ=6° - K_Q curves

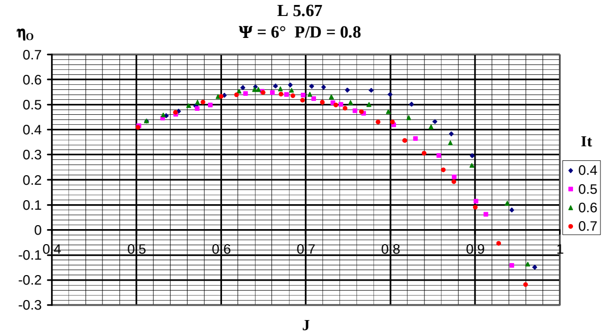

Fig. 7. Propeller 9701 - Ψ=6° - η_O curves

For the sake of comparison, in following figures 8-10 experimental results in correspondence to same testing conditions for propeller E9901 (P/D=1.0) are reported.

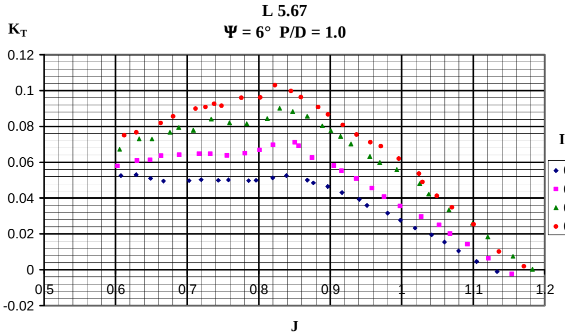

Fig. 8. Propeller 9901 - Ψ=6° - K_T curves

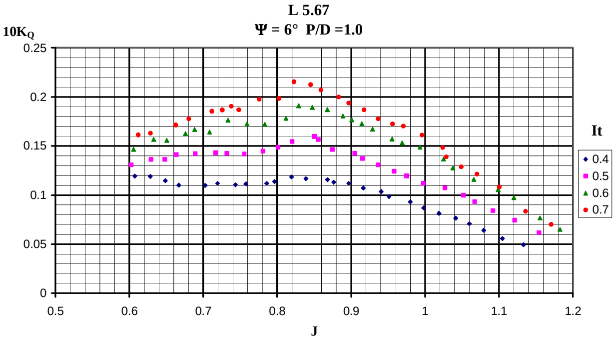

Fig. 9. Propeller 9901 - Ψ=6° - K_Q curves

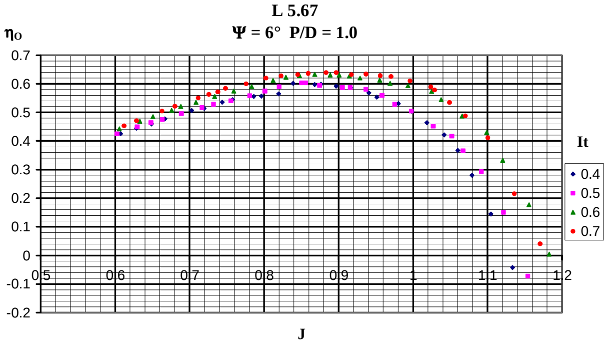

Fig. 10. Propeller 9901 - Ψ=6° - η_O curves

Finally, in following figures 11-13 experimental results in correspondence to same testing conditions for propeller E9702 (P/D=1.2) are reported.

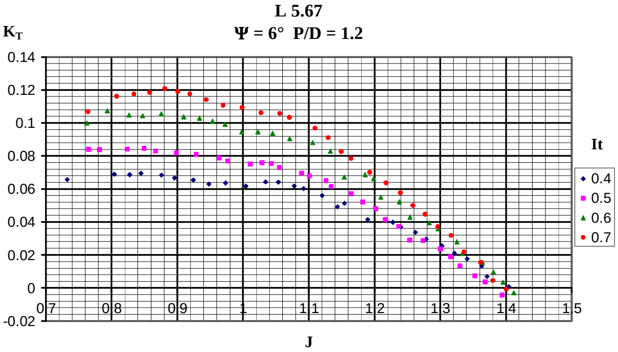

Fig. 11. Propeller 9702 - Ψ=6° - K_T curves

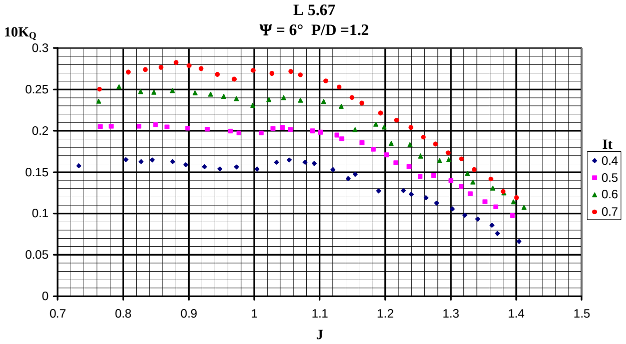

Fig. 12. Propeller 9702 - Ψ=6° - K_Q curves

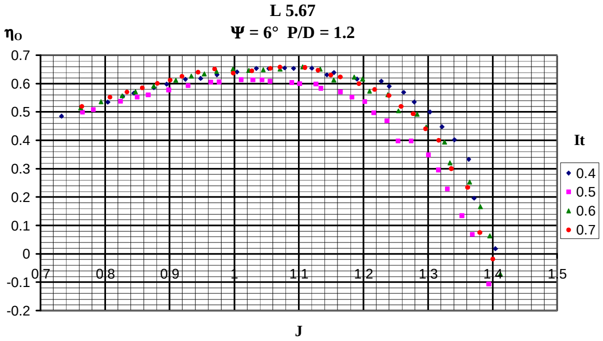

Fig. 13. Propeller 9702 - Ψ=6° - η_O curves

5. EXPERIMENTAL RESULTS ANALYSIS

The large amount of experimental data gathered has been re-analysed in order to better consider some characteristic parameters, i.e. immersion ratio I_T and longitudinal shaft inclination Ψ. In particular, thrust and torque coefficients have been evaluated considering a different nondimensionalization, according to formulations reported in the following.

For what regards longitudinal inclination, thrust measured by dynamometer is in the propeller shaft direction, therefore advance coefficient J_Ψ has been recalculated considering advance velocity component in the same direction, as represented in following figure 14, and according to equation 4:

$$J_\psi = \frac{V_A \cos\psi}{n\, D} \qquad (4)$$

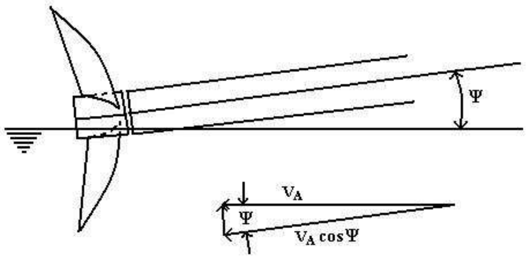

Fig. 14. Advance velocity in axial direction

As a result, characteristic curves for inclined shaft tests are translated towards left , and tend to collapse into a unique curve.

Regarding immersion coefficient, a different formulation has been introduced in [3], in order to better capture influence of propeller immersion on propeller characteristic curves. In particular, immersed propeller area $A_{O'}$ is considered in the new K_T and K_Q formulations, as follows:

$$K'_T = \frac{T}{\rho n^2 D^2 A_{O'}} \qquad K'_Q = \frac{Q}{\rho n^2 D^3 A_{O'}} \qquad (5)$$

where $A_{O'}$ is represented in following Figure 15:

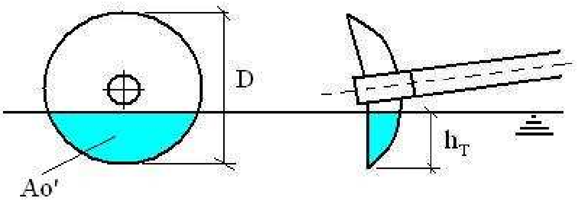

Fig. 15. Immersed propeller area $A_{O'}$

As a result of the two alternative nondimensionalization introduced, propeller curves obtained at different longitudinal shaft inclination and immersion ratio (figure 16) tend to collapse into a unique curve, as reported in following figure 17

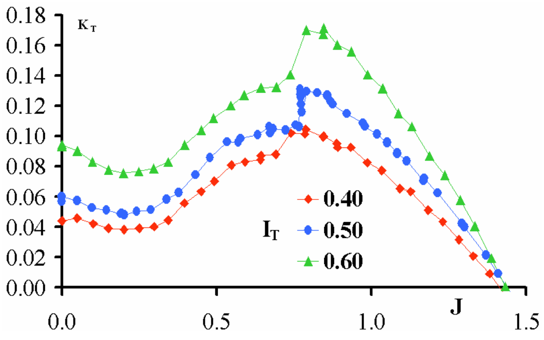

Fig. 16. Thrust coeficient KT (usual nondimensionalization)

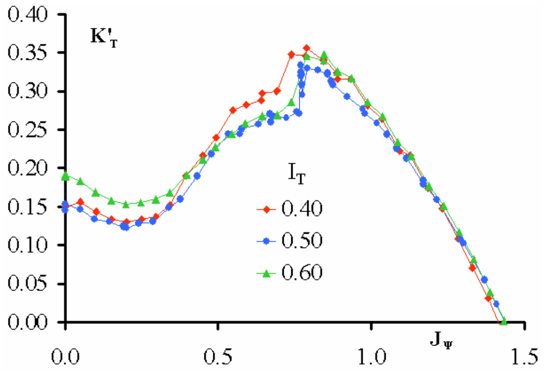

Fig. 17. Thrust coeficient K'T (SPP nondimensionalization)

As expected, different curves tend to collapse into a unique one, especially in correspondence to the partially ventilated regime before transition (higher values of the advance coefficient). This nondimensionalized version has been considered in order to obtain regression curves for K_T and K_Q, as reported in following paragraphs. Since different curves tend to collapse in a unique one in correspondence to values of the advance coefficient higher than the critical one, regressions refer only to this part. In particular, regressions are studied in order to relate K_T and K_Q coefficients to J_Ψ and P/D.

In following equations 6 and 7, linear regressions obtained are reported, while in equations 8 and 9 quadratic regressions are reported. In order to appreciate visually how these regression approximate experimental data, in figures 18-19 and 20-21 they are represented in graphical form.

$$K'_T = -0{,}51362 J_\psi + 0{,}63809(P/D) - 0{,}01018 \qquad (6)$$

$$10K'_Q = -0{,}64987 J_\psi + 1{,}11662(P/D) - 0{,}15068 \qquad (7)$$

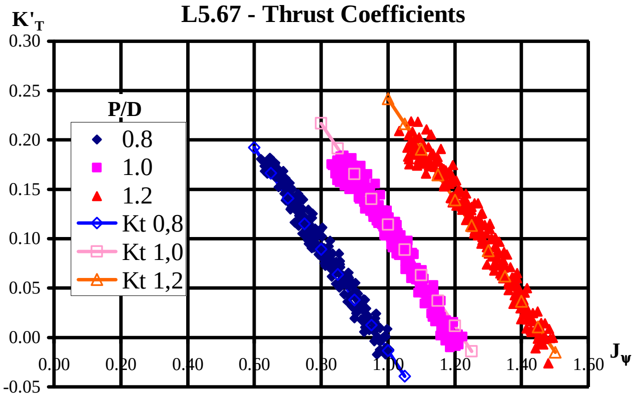

Fig.18. K'_T Linear Regression

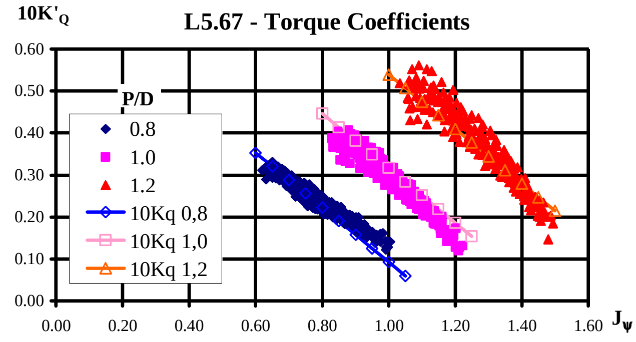

Fig.19. K'_Q Linear Regression

$$\begin{aligned} K'_T = &-0{,}61986 J_\psi + 0{,}14553(P/D) + \\ &+0{,}72956 J_\psi (P/D) - 0{,}3049 J_\psi^2 + \\ &-0{,}12523(P/D)^2 + 0{,}28459 \end{aligned} \qquad (8)$$

$$10K'_Q=-0{,}18468J_\psi-1{,}20569(P/D)+ +0{,}69548J_\psi(P/D)-0{,}56171J_\psi^2+ +0{,}80543(P/D)^2+0{,}75101 \qquad (9)$$

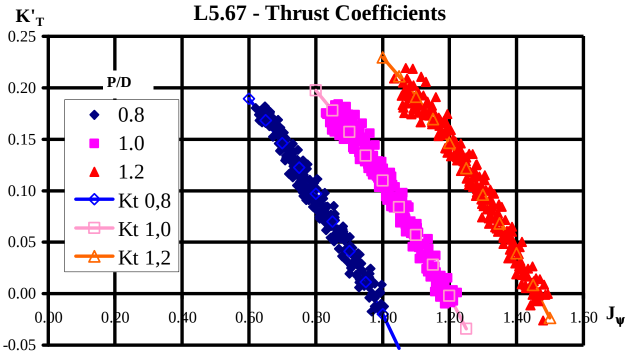

Fig. 20. K'$_T$ quadratic regression

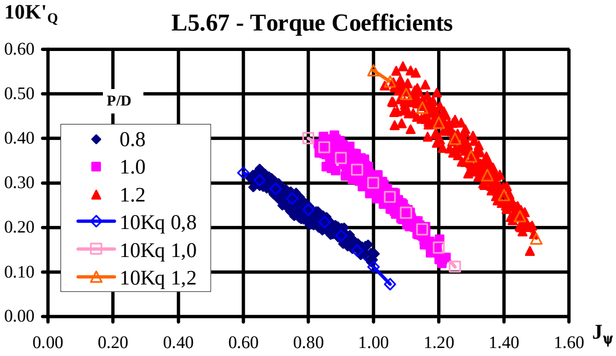

Fig.21. K'$_Q$ quadratic regression

As it can be seen from previous figures, quadratic regression can provide a slightly better fit of experimental data; nevertheless, linear regresssions still present considerably high R-squared values (0.956 and 0.913 for thrust and torque coefficient respectively, compared to 0.968 and 0.956 obtained for quadratic regressions).

In following figure 22, open water efficiencies obtained adopting K'$_T$ and K'$_Q$ values from quadratic regressions are reported.

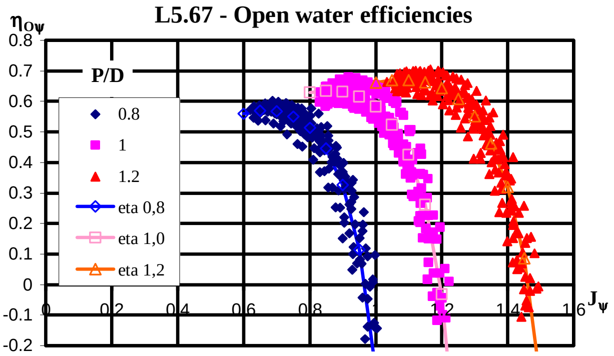

Fig.22. η$_O$ from quadratic regression

6. COMPARISON BETWEEN L4.68 AND L5.67 SERIES

Results from present work increase the wide database of experimental data already gathered in previous activities on 4-bladed propellers [5].

For the sake of completeness, in following equations 10 and 11 quadratic regressions obtained for 4.68 series are reproted, while in figures 23 and 24 K'$_T$ and K'$_Q$ are represented for all models tested together with related regression curves.

$$K'_T=-0{,}691625J_\psi+0{,}794973(P/D)+ 0{,}870696J_\psi(P/D)-0{,}395012J\psi^2+ -0{,}515183(P/D)^2 \qquad (10)$$

$$10K'_Q=-0{,}300453J_\psi+0{,}543738(P/D)+ 0{,}877638J_\psi(P/D)-0{,}649314J_\psi^2+ -0{,}208974(P/D)^2 \qquad (11)$$

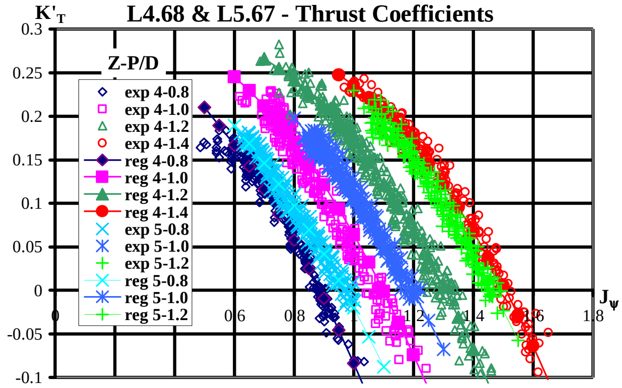

Fig.23. L4.68 & L5.67 K'$_T$ values

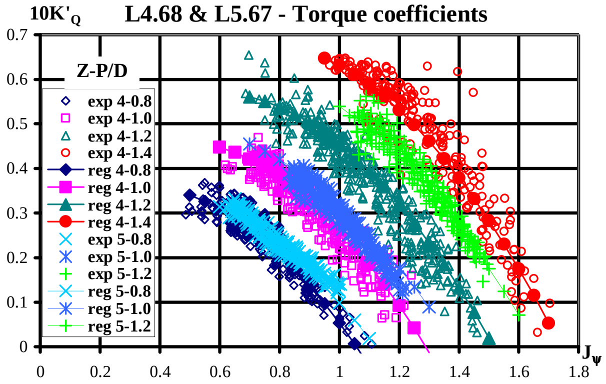

Fig.24. L4.68 & L5.67 K'$_Q$ values

From the point of view of the statistycal analysis, regressions obtained for the 4-bladed propellers present slightly lower R-squared values, especially for what regards torque coefficient (0.961 and 0.923 respectively), which result from a larger spread of data.

This result is partly due to the larger amount of data available for the 4-bladed propellers, which have been tested during years in different experimental facilities (Naples towing tank, Genoa Cavitation Tunnel, NRC-IMD Towing Tank in St.John's, Newfoundland, Canada) and not only at Genoa Cavitation Tunnel as for the 5-bladed propellers. Moreover, it is likely that the presence of an additional propeller with P/D 1.4 can result in a slightly lower R-squared value.

From analysis of these data it can be seen that, as expected, thrust and torque coefficients increase with P/D for both propeller series; however, a slightly different behaviour between 4-bladed and 5-bladed propeller is evidenced, since thrust and torque coefficients for the latter tend to increase more in correspondence to same increments of P/D ratio, contrarily to what could be expected since propeller characteristics (blade section profiles, A_E/A_O, etc.) are similar.

A possible explanation of this phenomenon (still to be confirmed) may be related to the different functioning of propellers with odd or even blade number. In particular, propellers with an even number of blades present a symmetrical functioning, in which blade surface entering into water is always similar to blade surface coming out of water, while for propellers with an odd number of blades an asymmetrical functioning, with a higher instantaneous blade surface can be experienced. It is likely, however, that mean force and torque are not considerably modified by this behaviour, since higher and lower instantaneous thrust and torque tend to compensate each other, and problems related to odd or even blade number are limited only to different values of fluctuating forces.

Another reason for this behaviour could be the different spacing between blades and different chord lengths, which can result in a modified flow, with shifting of the apparent advance coefficient.

This anomalous behaviour is still to be investigated, and a better insight could be gained by means of additional tests on propellers with different blade numbers (e.g. 3 and 6), maintaining constant remaining parameters.

7. INFLUENCE OF WEBER NUMBER

During the experimental campaign carried out in [7], whose results are summarized in the present work, all tests have been carried out with an almost constant advance velocity in correspondence to J_{CR} value, varying propeller revolutions in order to modify advance coefficient value, according to testing procedure usually adopted at DINAV cavitation tunnel for surface piercing propellers. This test procedure does not provide a deep insight in the analysis of Weber number influence on J_{CR} value, since Weber number itself is not varied systematically. Nevertheless, tests carried out on the three different models with variable P/D ratio lead to three groups of points in the graph W'_E- J_{CR} (figure 25), where J_{CR} experienced in different tests are reported as a function of Weber number.

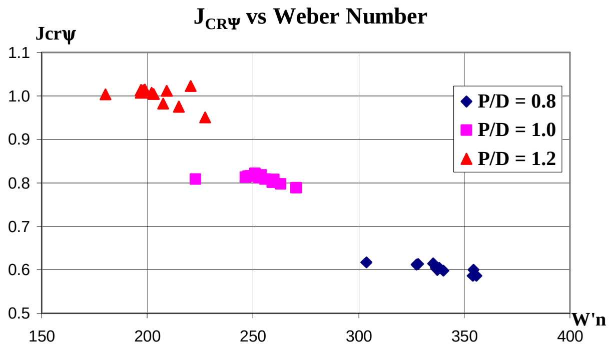

Fig.25. Critical advance coefficient vs Weber number

Weber number utilized in figure 25 is the one proposed by Shiba [10], according to following equation:

$$W'_E = \sqrt{\frac{n^2 D^3}{\kappa}} \qquad (12)$$

Lower limit usually suggested for Weber number in order to avoid scale effects is 180-200 [10]. Even if this experimental campaign was not dedicated to the analysis of this phenomenon, an implicit confirmation of it can be found by the analysis of previous figure 25. In particular, it can be seen that a higher spread of data has been experienced for propeller with P/D = 1.2, whose transition happens at W'_E values around 200, while for remaining models with P/D = 0.8 and P/D = 1.0, for which transition is experienced in correspondence to higher W'_E values, data is considerably less spread.

8. CONCLUSIONS

In present work, experimental results obtained from a systematic analysis of a 5-bladed surface piercing propeller series have been presented.

On the basis of these results, regression curves for usual K_T and K_Q coefficients in correspondence to values of the advance coefficient higher than the critical one have been evaluated and are reported.

This analysis further increases the large experimental database on SPP developed by DINAV and DIN in previous years on the 4-bladed series L4.68; it is believed that these data can provide a useful source of information for designers in the field of SPP, where a significant lack of data still exist nowadays despite the ever increasing number of applications..

A different influence of P/D ratio on propeller characteristic curves for the two series emerged from the comparison of present and previous results; reasons for it are still to be investigated by means of further analyses, which could be extended to propellers with different blade numbers.

Weber number influence on propeller characteristic curves has not been specifically addressed by this study, nevertheless a partial confirmation of what is reported in previous studies has been obtained.

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