Fourth International Symposium on Marine Propulsors
smp'15, Austin, Texas, USA, June 2015

A Panel Method for Prediction of Performance of Ducted Propeller

Hongyang Fan[1], Ye Tian[2], Spyros A. Kinnas[3]

[1,2,3] Ocean Engineering Group, Department of Civil, Architectural and Environmental Engineering
The University of Texas at Austin, Austin, TX 78712, USA

ABSTRACT

A perturbation potential based inviscid panel method for the performance prediction of ducted propellers is proposed and implemented. The method has been found to predict very well the thrust and torque on ducted propellers over a wide range of operating conditions, while requiring significantly less computational time than a full-blown RANS simulation. Nonetheless, the prediction of ducted propeller forces is only one of the objectives in developing this panel method. The authors are also interested in more detailed results, such as the pressure distribution on the propeller blades. Accurate pressure distribution not only as an important validation of the method, but is also essential for cavitating flow simulations.

In this paper, full-blown RANS simulations for different types of ducted propellers are performed with sufficient spatial resolution. The panel method is also used to simulate the same cases. The predicted forces and pressure distributions on the blade surface, from the two methods, are compared with each other, as well as with existing experiments.

Keywords

Panel method, wake alignment, force, pressure distribution

1 INTRODUCTION

Ducted propellers have been, for a long time, a viable alternative of propulsion in the ocean engineering community. At low speeds, or at high thrust coefficients, ducted propellers can have much higher efficiency than open propellers. Thus applications of ducted propellers or thrusters can be found in many types of ships which are often highly loaded or moving slowly.

The panel method has shown great advantage over other numerical tools in terms of performance prediction of ducted propellers. Firstly unlike the Vortex Lattice Method (VLM) which simplifies the propeller blades into lifting surfaces, the panel method can maintain the real shape of the blade as much as possible. In addition, the panel method is far more efficient than the commonly used Reynolds-averaged Navier-Stokes (RANS) simulation in the sense of computational resources and duration. Generally, the panel method strikes a good balance on accuracy and computational efficiency.

Hess et al. (1964) published the pioneering work of panel method. Since then, a large number of panel codes have been established. Subsequently, Gibson et al. (1973) Hess et al. (1985) developed the panel method for the specific application of propellers. Morino et al. (1974) introduced a panel method based on Green's formulation in which the primary unknown was the potential. J.-T. Lee (1987) carried out a comprehensive investigation of panel methods for a most suitable formulation for simulation of marine propellers.

A good wake alignment scheme is of significance such that the trailing edge wake surface can be reasonably represented. Greeley et al. (1982) introduced a fast wake alignment scheme (PSF-2 type alignment). Pyo et al. (1997) presented a fully aligned wake model with biquadratic dipole panels. Lee et al. (2004) developed a 3D wake model for marine propellers with an emphasis on the modeling the tip vortex cavity. Tian et al. (2012) proposed and implemented a full wake alignment model based on a pseudo-unsteady scheme for a low-order panel method.

It is a common practice to couple the panel code with a boundary layer solver to include the effects of viscosity on blades and duct. Drela (1989) coupled an inviscid solver based on a vorticity based panel method with a two-dimensional integral boundary layer formulation for airfoils. Milewski (1997) developed a 3-D fully simultaneous viscous/inviscid interactive scheme by coupling a potential based panel method and the 3-D integral boundary layer equations, for 3D wetted hydrofoil and duct flows. Hufford (1992, 1994) coupled a three-dimensional panel method with a 2-D boundary layer solver in a strip wise manner, where the 2D boundary layer sources were replaced by 3D sources. Sun (2008) simplified Hufford's method by assuming boundary layer sources as two-dimensional sources and neglecting the effects from other strips. Yu (2012) proposed a scheme of including the effects of boundary layer sources from other strips using three dimensional boundary layer sources. Purohit (2013) improve the 3-D viscous-inviscid interactive scheme of Yu (2012) by including the important interaction effects from other strips.

In this paper, the full wake alignment scheme proposed by Tian et al (2012) is improved by taking into consideration the effects of the sources and dipoles on duct surface and the dipoles along the duct wake surface. The improved panel method is then validated against full-blown RANS simulation as well as existing experiments in two different cases: ducted propeller with a round blade tip and ducted propeller with a square blade tip. The effects of viscosity are not included at this stage. Correlations of the general force performance and pressure distribution on blade surface have been conducted and it was found that the current method can render accurate prediction of the ducted propeller performance with great efficiency.

2 FORMULATION

The velocity flow field is decomposed into two components: inflow velocity and perturbation velocity, written as follows:

$$\mathbf{q} = \boldsymbol{U}_\infty + \boldsymbol{u} \tag{1}$$

Where $\mathbf{q}$ is the total velocity, $\boldsymbol{U}_\infty$ is the inflow velocity, and $\boldsymbol{u}$ is the perturbation velocity due to presence of obstacles.

2.1 Governing Equations

The methodology applied in this study is *based* on the inviscid potential flow theory:

$$\mathbf{u} = \nabla\phi \tag{2}$$

where φ is the perturbation potential. The perturbation velocity field, therefore, is governed by the Laplace Equation:

$$\nabla^2\phi = 0 \tag{3}$$

If the inflow is also irrotational, we can also define the total potential Φ as follows:

$$\mathbf{q} = \nabla\phi + \boldsymbol{U}_\infty = \nabla\Phi \tag{4}$$

Applying Green's second identity, the Laplace equation can also be written as the following boundary integrated form:

$$2\pi\varphi_p = \iint_{S_H}\left[\phi_P\frac{\partial G(p,q)}{\partial \boldsymbol{n}_q} - \frac{\partial \phi_P}{\partial \boldsymbol{n}_q}G(p,q)\right]dS + \int_{S_W}\Delta\phi_w(y_p)\frac{\partial G(p,q)}{\partial \boldsymbol{n}_q}dS \tag{5}$$

Where S_H represents the surface of hydrofoil or propeller blades and S_W represents the surface of trailing edge wake. $G(p,q)$ is the Green's function, which is defined as $1/R(p,q)$ in 3D, and R is the distance between the two points p and q. A low-order panel method using constant dipole panels is adopted to solve the integrated equation.

2.2 Boundary Conditions

(i). Kinematic Boundary Condition

Applying the kinematic boundary condition to the solid surface, we obtain the following:

$$\frac{\partial\phi}{\partial\boldsymbol{n}} = -\boldsymbol{U}_\infty\cdot\boldsymbol{n} \tag{6}$$

(ii). Pressure Kutta Condition

At trailing edge, $\Delta\phi_w$ is unknown, which is subjected to the pressure Kutta condition:

$$p_W^+ = p_W^- \tag{7}$$

where the + sign denotes the suction side panel, and the – sign denotes the pressure side panel. The physical meaning here is that free vortex sheets cannot bear pressure jump.

For steady state problem, (7) leads to the modified Morino-Kutta condition:

$$\Delta\phi_w = \phi_w^+ - \phi_w^- + \boldsymbol{U}_\infty\cdot\boldsymbol{r}_{TE} \tag{8}$$

where $\boldsymbol{r}_{TE}$ is the vector from the control point of (-) panel to the (+) panel at the trailing edge.

For unsteady problem in 2D, or even steady problem in 3D, (7) has to be enforced through the unsteady Bernoulli equation:

$$\frac{\partial(\Phi^+ - \Phi^-)}{\partial t} + \frac{1}{2}(q^+)^2 - \frac{1}{2}(q^-)^2 = 0 \tag{9}$$

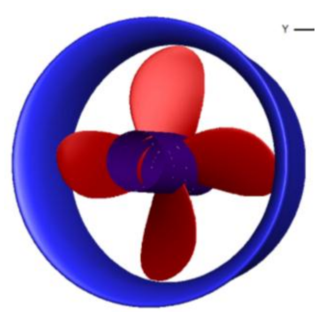
An iterative scheme named Iterative pressure Kutta condition (IPK) has to be applied in order to enforce (9).

3 RESULTS AND DISCUSSION

In order to validate the efficiency and accuracy of the panel method, simulations through RANS and also the panel method were performed for two different ducted propellers: (1) DYNE's propeller, which is a 4 bladed propeller with round blade tip, bounded by a duct with sharp trailing. (2) KA4-70 propeller, which is a 4 bladed propeller with square blade tip, bounded by modified 19A duct.

3.1 Application to Ducted Propeller with Round Tip

The panel method is firstly applied to the case where the DYNE's propeller, which is a 4 bladed propeller with round tip, is bounded by a sharp trailing edge duct. The design advance ration J_s of this ducted propeller is around 0.40. An improved full wake alignment (FWA) scheme is adopted.



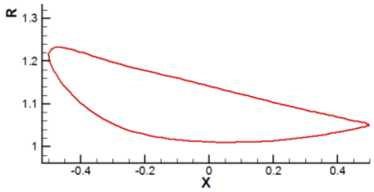


Figure 1 Geometry of the ducted propeller with round blade tip and sharp trailing edge duct

RANS simulations of the same propeller are carried out with commercial codes *Star-CCM+* and *FLUENT*, for Js = 0.3, 0.4, 0.5, 0.6 and 0.7. K-ω SST turbulence model is adopted. QUICK scheme is used for spatial discretization, and SIMPLEC scheme is applied for pressure correction. 5 million polyhedral cells are used to simulate a quarter of the whole domain with periodic boundary condition. Structured grids are constructed around the blade, duct as well as the wake area. It took over 30 hours on 32 Intel Xeon 2.54 GHz CPUs for the residuals well converged.

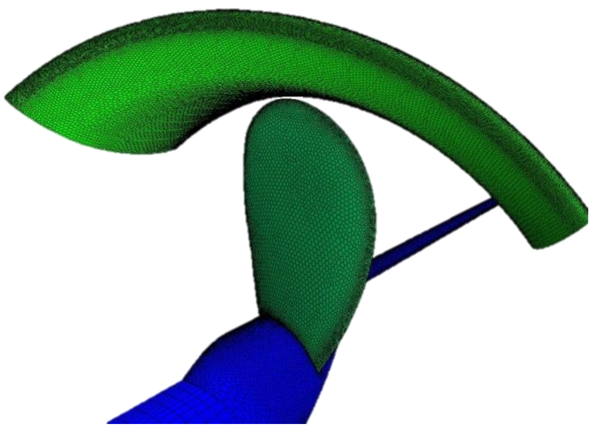


Figure 2 Gridding of the RANS simulation

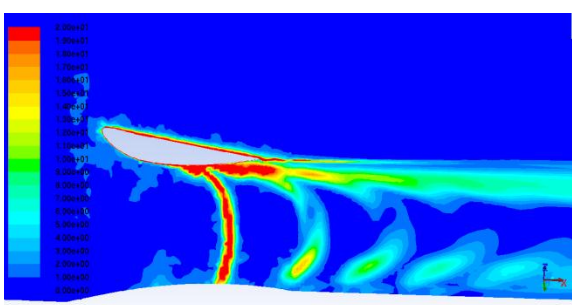


Figure 3: Contour of vorticity magnitude in the RANS simulation

Fig. 3 shows at design loading the contour of vorticity magnitude in one periodic interface. High vorticity magnitude is observed as expected around the blade, duct, hub as well as the trailing edge wake. The characteristic of periodicity is also observed.

For the panel method, 80×20(chordwise×spanwise) and 200×80 (chordwise×circumferential) panels were used to respectively resolve the blade surface and duct surface. It took about 30 minute on a single core of the same type CPU as that in the RANS case to complete the run.

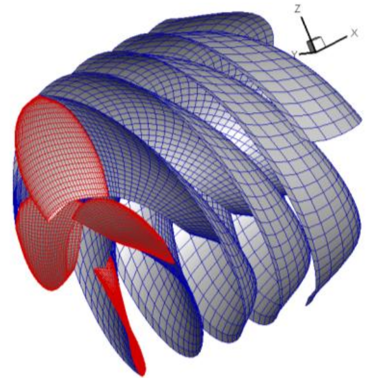


Figure 4: Geometry of the wake at the 10th revolution of simulation.

Fig. 5 shows the force performance of the ducted propeller from the panel method, the RANS simulation as well as experimental measurements. KT and 10KQ represent the propeller thrust and the torque, respectively. The performance predicted by the panel method is in good agreement with the RANS simulations and experiments.

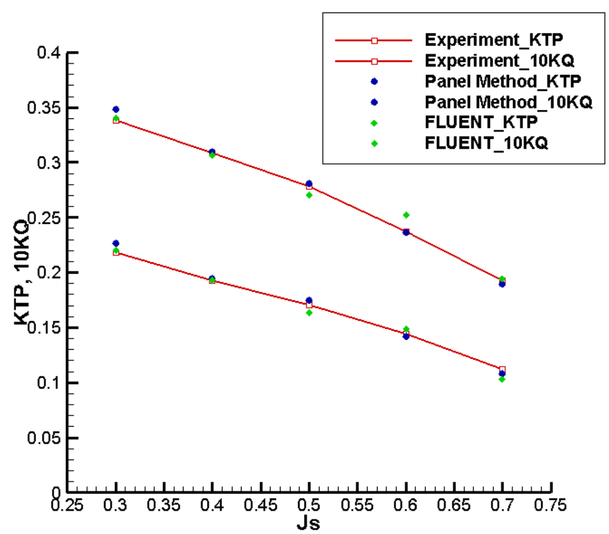


Figure 5: Comparison of force performance between the results from RANS and panel method.

Fig.6- Fig.8 represent the detailed correlations of pressure distribution on the propeller blades under three different loading condition: high loading condition (J_s=0.30), design loading condition (J_s=0.40) and low loading condition (J_s=0.50). For each loading condition, two blade strips, r/R=0.65, 0.80 are selected for comparison. Clearly the predictions of pressure distribution by the panel method are

in very good agreement with the RANS simulations for different blade strips at different loading conditions. The authors believe that coupling the current panel method with a boundary layer solver will bring the results closer to those from RANS.

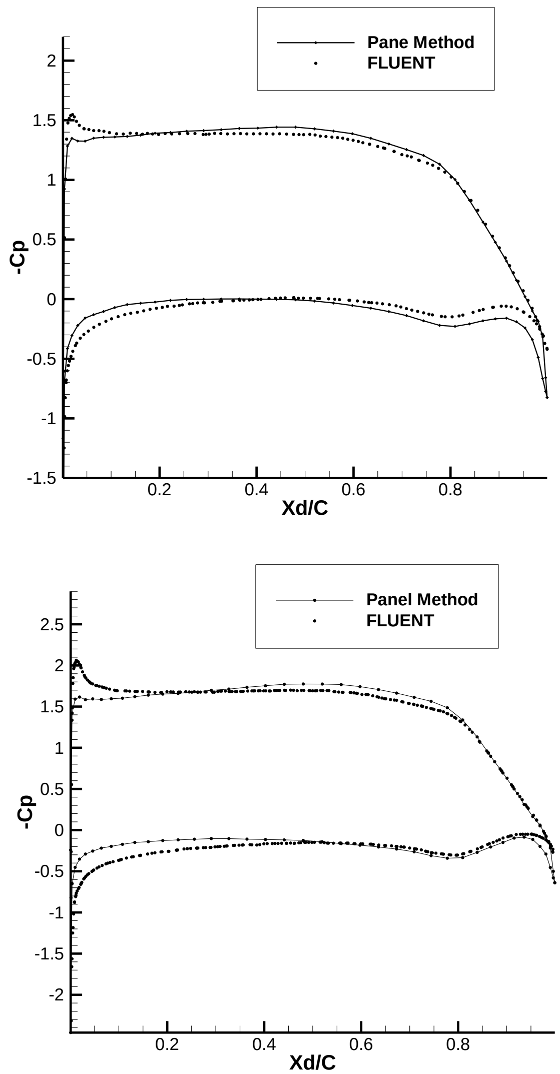


Figure 6: Comparisons of the pressure distributions predicted by RANS and the panel method at blade strips r/R=0.65 (upper), 0.80 (lower) for high loading (J_s=0.30)

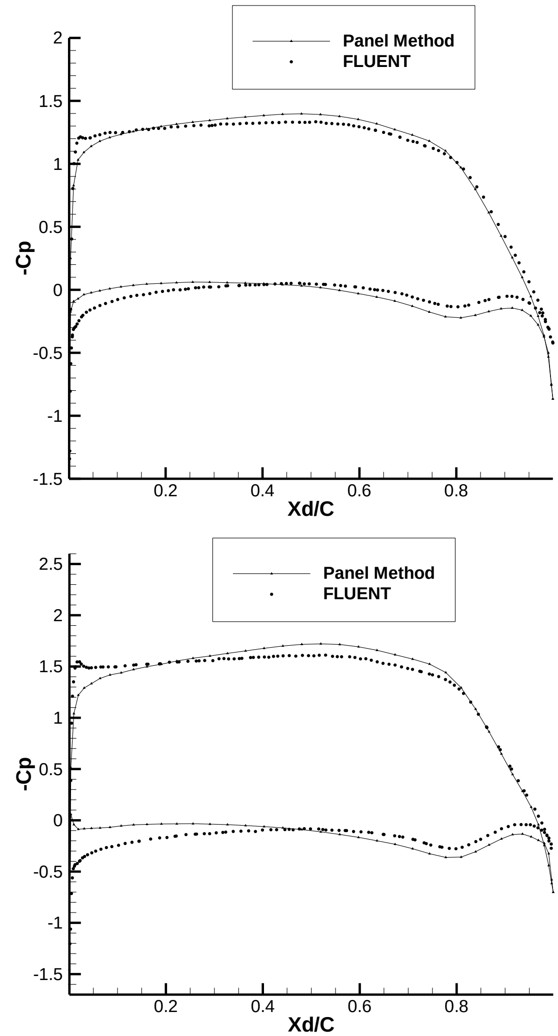
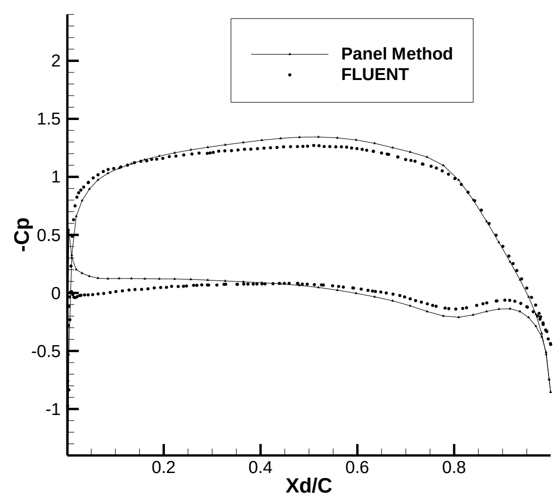


Figure 7: Comparisons of the pressure distributions predicted by RANS and the panel method at blade strips r/R=0.65 (upper), 0.80 (lower) for design loading (J_s=0.40)



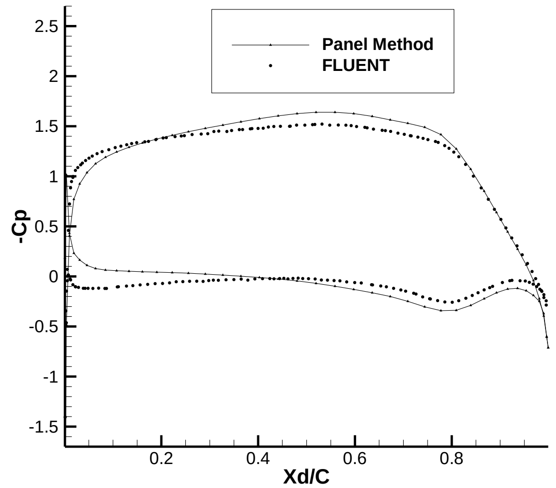


Figure 8: Comparisons of the pressure distributions predicted by RANS and the panel method at blade strips r/R=0.65 (upper), 0.80 (lower) for low loading (J_s=0.50)

3.2 Application to Ducted Propeller with Square Tip

The present method is applied to the case where KA4-70 propeller, which is a 4 bladed propeller with P/D=1.0 and a square tip, is bounded by a sharp trailing edge duct. Originally the duct has a round trailing edge, which the panel method cannot resolve because of the resulted recirculation zone. The duct shape is modified by MARIN such that it has a sharp trailing edge while at the same its performance is not much influenced. The design advance ration J_s of this ducted propeller is around 0.50.

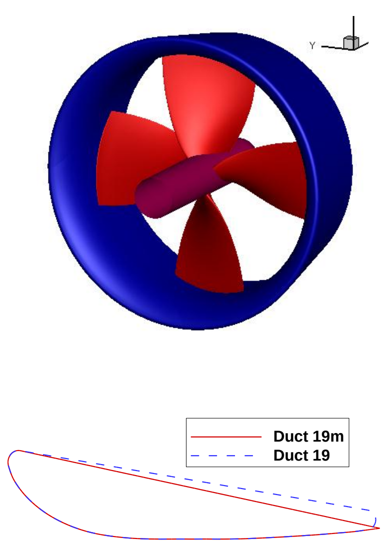


Figure 9: Geometry of the ducted propeller with square blade tip and sharp trailing edge duct

RANS simulations of this ducted propeller are conducted in *FLUENT*, for Js = 0.3, 0.4, 0.5, 0.6 and 0.7. The physical models and computation data are presented in Table 1.

Table 1 Physical Model and Computation Data for RANS Simulation

Cell number	6 million
Reynolds number	1.0e6
Turbulence Model	Standard k-ε
Pressure Correction Scheme	SIMPLEC
Spatial discretization	QUICK
CPU type	Intel Xeon 2.54 GHz CPU
Total time for calculation	Over 40 hours (32 CPUs)

For the panel method, 80×30(chordwise×spanwise) and 200×80 (chordwise×circumferential) panels were used to respectively resolve the blade surface and duct surface. It took about 30 minute on a single core of the same type CPU as that in the RANS case to complete the run.

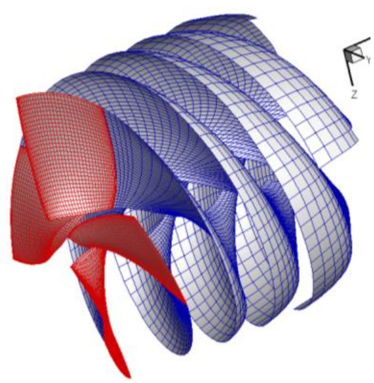


Figure 10: Geometry of the wake at the 10th revolution of simulation.

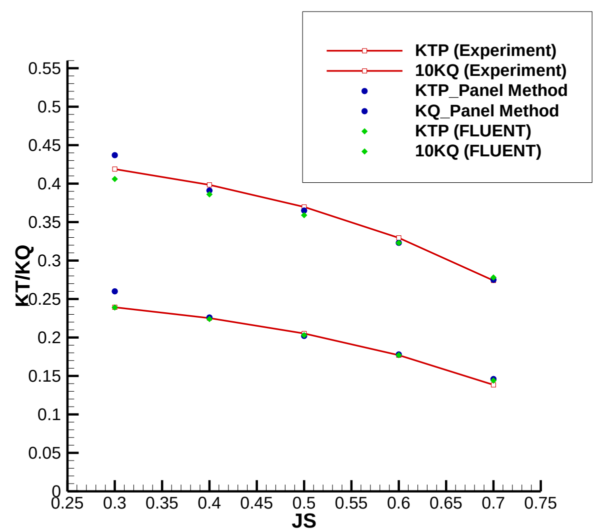


Figure 11: Comparison of force performance between the results from RANS and panel method.

The correlation in Fig.11 clearly indicates that the performance predicted by the panel method is in good agreement with the RANS simulations and experiments.

Fig.12- Fig14 represent the detailed correlations of pressure distribution on the propeller blades under three different loading condition: high loading (J_s=0.40), design loading (J_s=0.50) and low loading (J_s=0.60). For each loading condition, two blade strips, r/R=0.65 and 0.86 are selected for comparison. Again the predictions of pressure distribution by the panel method are in very good agreement with the RANS simulations for different blade strips at different loading conditions.

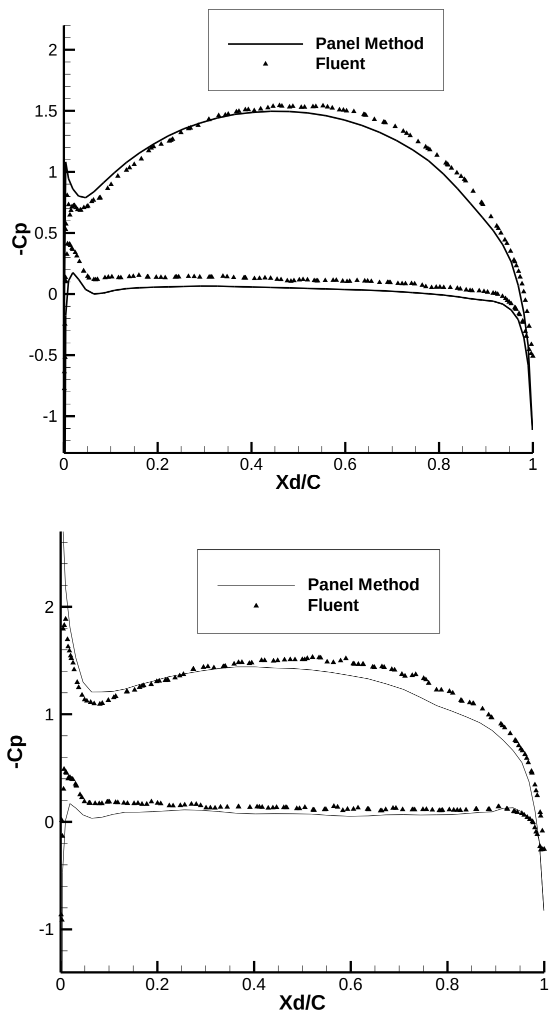


Figure 12: Comparisons of the pressure distributions predicted by RANS and the panel method at blade strips r/R=0.65 (upper), 0.86 (lower) for high loading (J_s=0.40)

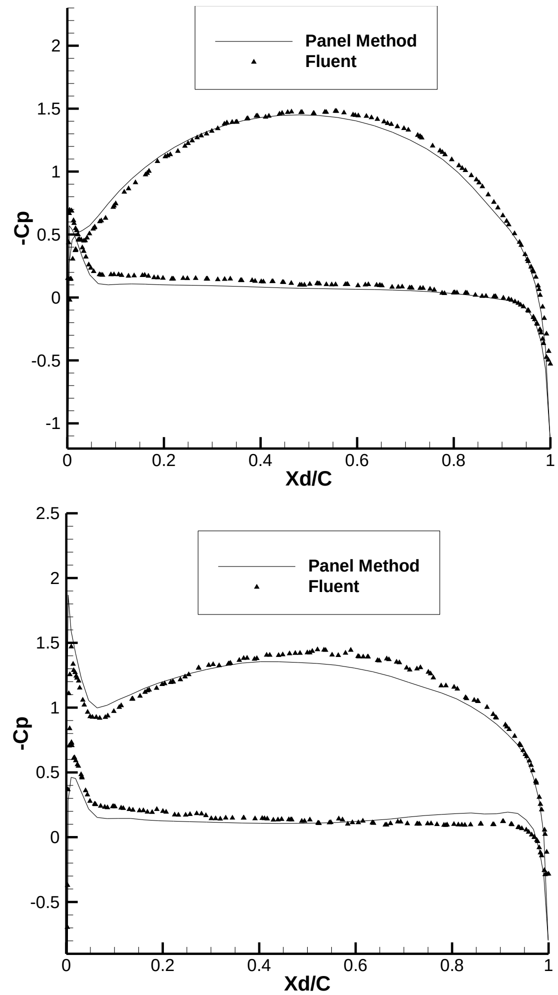
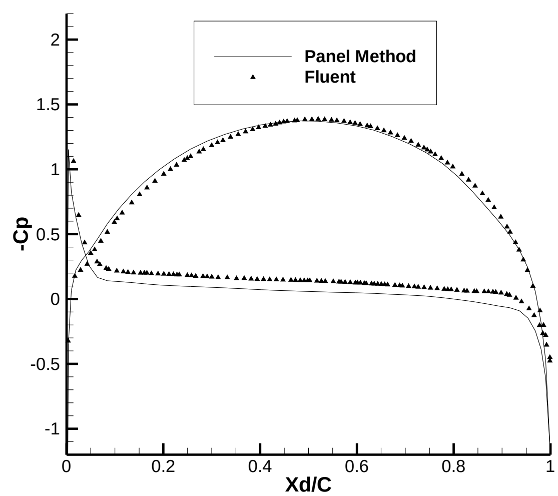


Figure 13: Comparisons of the pressure distributions predicted by RANS and the panel method at blade strips r/R=0.65 (upper), 0.86 (lower) for design loading (J_s=0.50)



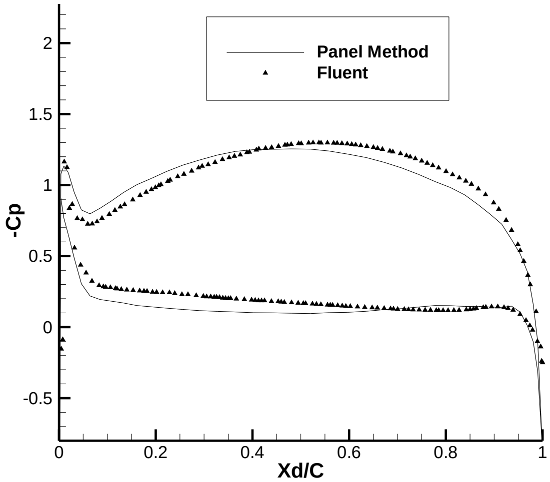


Figure 14: Comparisons of the pressure distributions predicted by RANS and the panel method at blade strips r/R=0.65 (upper), 0.86 (lower) for low loading (J_s=0.60)

4 CONCLUSIONS AND FUTURE WORK

A perturbation potential based panel method for prediction of performance of ducted propellers was proposed and implemented. For detailed correlation of pressure distribution on blade surface, full-blown RANS simulation was also carried out in commercial FLUENT code.

The panel method was first validated with the case of ducted propeller with round blade tip. The force predicted by the current method is compared with that from RANS simulation and experiment. Although the panel method slightly over-predicted the thrust and torque, the results agreed largely well. Good correlation of pressure distribution on blade surface was also found at different blade strips for different loading conditions between the current method and RANS simulation.

The present method is then applied to the more challenging case of ducted propeller with a square tip. By adopting the scheme of full wake alignment, the method was able to render accurate prediction of the general performance. Its accuracy is again validated through the correlation with RANS simulation on pressure distribution on blade surface.

It is worth noting that the current method takes about 1/80 of the CPU time, while using only one processor versus 32 processors used in the case of full blown RANS simulations. In addition, the time devoted in gridding for the full blown RANS can take several days, while it is negligible in the case of the present hybrid method.

Further efforts will be devoted to coupling the panel method with an integral boundary layer solver to include the effects of viscosity in a three-dimensional way, as described in (Purohit 2013).

ACKNOWLEDGMENTS

Support for this research was provided by the U.S. Office of Naval Research (Contract No. N00014-07-1-0616, Contract N00014-10-1-0931 and N00014-14-1-0303) and Phases V, VI and VII of the "Consortium on Cavitation Performance of High Speed Propulsors" with the following members: American Bureau of Shipping, Daewoo Shipbuilding and Marine Engineering Co. Ltd., Kawasaki Heavy Industry Ltd., Rolls-Royce Marine AB, Rolls-Royce Marine AS, Samsung Heavy Industries Co. Ltd., SSPA AB, Andritz Hydro GmbH, Wärtsilä Netherlands B.V., Wärtsilä Norway AS, Wärtsilä Lips Defense S.A.S., and Wärtsilä CME Zhenjiang Propeller Co. Ltd., Steerprop Ltd.

REFERENCES

Hess, J. L. and Smith, A. M. O.(1964), "Calculation of Nonlifting Potential Flow About Arbitrary Three-Dimensional Bodies," Journal of Ship Research, Vol. 8, No.2.

Gibson, I. S. and Lewis, R. I. (1973), "Ducted Propeller Analysis by Surface Vorticity and Actuator Disc Theory, " in Proceedings, Symposium on Ducted Propellers, The Royal Institution of Naval Architects, Teddington, England.

Hess, J. L. and Valarezo, W. O. (1985), "Calculation of Steady Flow About Propellers by Means of a Surface Panel Method, " in Proceedings 23rd Aerospace Sciences Meeting, AIAA, Reno, Nev..

Morino, L. and Kuo, C. C. (1974), "Subsonic Potential Aerodynamics for Complex Configurations: A General Theory," AIAA Journal, Vol. 12, No.2, 191-197.

Lee, J. T. (1987), "A Potential Based Panel Method for The Analysis of Marine Propellers in Steady Flow," PHD dissertation, Department of Ocean Engineering, MIT.

Greeley, D. S. and Kerwin, J. E. (1982), "Numerical methods for propeller design and analysis in steady flow," Transactions of Society of Naval Architects & Marine Engineers, Vol. 90, 415-452.

Pyo, S. and Kinnas, S. A. (1997), "Propeller wake sheet roll-up modeling in three dimensions," Journal of Ship Research, Vol.41, No. 2, 81–92.

Lee, H. and Kinnas, S. A. (2004), "Application of a boundary element method in the prediction of unsteady blade sheet and developed tip vortex cavitation on marine propellers," Journal of Ship Research, Vol.48, No.1, 15–30.

Tian, Y. and Kinnas, S. A. (2012), "A Wake Model for the Prediction of Propeller Performance at Low Advance

Ratios", International Journal of Rotating Machinery, special issue: Marine Propulsors and Current Turbines: State of the Art and Current Challenges.

Drela, M. (1989), "XFOIL: An analysis and design system for low Reynolds number airfoils," Lecture Notes in Engineering, Vol. 54, Low Reynolds Number Aerodynamics, New York.

Milewski, W. M. (1997), "Three-dimensional viscous flow computations using the integral boundary integral equations simultaneously coupled with a low order panel method," PHD dissertation, Department of Ocean Engineering, MIT.

Hufford, G. S. (1992), "Viscous flow around marine propellers using boundary layer strip theory," Master thesis, MIT.

Hufford, G. S., Drela, M. and Kerwin, J. E. (1994), "Viscous flow around marine propellers using boundary layer strip theory," Journal of Ship Research, Vol 38(1), 52–62.

Sun, H. (2008), "Performance Prediction of Cavitating Propulsors Using a Viscous/Inviscid Interaction Method," PHD dissertation, CAEE, UT Austin.

Yu. X. (2012), "Three dimensional viscous/inviscid interactive method and its application to propeller blades," Master thesis, CAEE, UT Austin.

Purohit, J. (2013), "An Improved Viscous-Inviscid Interactive Method and its Application to Ducted Propellers," Master thesis, CAEE, UT Austin.