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Four Quadrant Thrust and Torque Prediction of INSEAN E-1619 Generic Submarine Propeller for Submarine Maneuvering Simulations

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ABSTRACT

DARPA (Defence Advanced Research Projects Agency) Suboff submarine and INSEAN (Istituto Nazionale per Studi ed Esperienze di Architettura Navale) E1619 generic submarine propeller are widely used for numerical studies of submarine propulsion for forward speed. To use in ship maneuvering simulations, it is necessary to know the propeller thrust and torque characteristics over the entire region of propeller operations. This study is focused on the computational prediction of the four quadrant data of E1619 propeller. Numerical calculations are made by the Computational Fluid Dynamics (CFD) code ANSYS Fluent. The investigation is carried out with the seven bladed submarine propeller model INSEAN E1619 and the generic submarine model DARPA Suboff AFF8 form. Computations are validated by the published experimental data of the propeller for forward speed and forward propeller rotation and the rest of the quadrants are predicted numerically. Four quadrant Fourier coefficients for the propeller are presented.

Keywords

Submarine, propeller, four quadrant, CFD, Computational Fluid Dynamics, DARPA Suboff, INSEAN E1619

1 INTRODUCTION

Hydrodynamic performance of the proposed propeller is a requirement at the preliminary design phase of a ship. Open water curves of the propeller is often sufficient for performing preliminary powering estimates, however to conduct ship performance simulations such as for manoeuvering situations or astern conditions, four quadrant data is required (Roddy et al., 2006). Due to the available data, thanks to the scientists such as (Lammeren et al., 1969) and (Oosterveld, 1970) one of the most preferred subcavitating open-propeller series is the Wageningen B-Screw Series also for manoeuvering simulations of submarines.

Hydrodynamic properties of a propeller in off-design conditions should be investigated in two steps, first determining the suitable operation conditions non-dimensionalized with hydrodynamic pitch angle (β) and the second step is to solving or measuring the force and moment of the propeller based on computational or experimental fluid dynamics methods.

The aim of this paper is to present numerically computed four quadrant data of INSEAN E1619 propeller, which is computational parameters are defined in accordance to DARPA Suboff's operational conditions

Kawamura et al. (2004) comparatively analyzed different turbulence models for the prediction of open water performance for a conventional propeller. Later Li (2006) estimated open water characteristics of a highly skewed model propeller employing *k-ω* turbulence model and validated the study with experimental data. Gao et al. (2012) simulated numerically the unsteady viscous flow around an Autonomous Underwater Vehicle (AUV) with propellers by using the Reynolds-averaged Navier-Stokes (RANS) equations, shear-stress transport (SST) *k-ω* model and Pressure with Splitting of Operators (PISO) algorithm based on sliding mesh. The hydrodynamic characteristics of an AUV with propellers such as, resistance, pressure and velocity were reflected well the real ambient flow field of the AUV. Then, the semi-implicit method for pressure-linked equations (SIMPLE) algorithm was used to compute the steady viscous flow field. The computational results agreed well with the experimental data, showing that the numerical method has a good accuracy in the prediction of hydrodynamic performance of a propeller (Gao et al. 2012). A detailed literature review on the prediction of open water performance of propellers can be found in 26th ITTC (2011). The DARPA Suboff AFF8 with the E1619 has been studied by several researchers to investigate characteristics of self propulsion point (Chase, 2012, Chase and Carrica, 2013), cycle-to-cycle blade loading (Liefvendahl and Toerng, 2011), hull interactions (Alin et al., 2010) and hydro-acoustic properties by (Ozden et al, 2016)

Firstly a validation study has been carried out for open water hydrodynamic characteristics of E1619 generic submarine propeller and compared with the experimental results published by Di Felice et al. (2009). Suboff

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computations followed by self-propulsion analysis propelling both ahead and astern. In combination with the listed computations, critical hydrodynamic pitch angle (β) values are determined with a sensitivity of the propellers actual design conditions which covers the most important points of interest such as crash-back, crash-ahead, self-propulsion points ahead and astern. Change of thrust and torque coefficients over four quadrants is graphed and 30 harmonics of Fourier coefficients propeller data were presented.

2 GEOMETRY OF BODIES

Details of INSEAN E-1619 propeller and DARPA Suboff generic submarine geometries are as follows.

2.1 INSEAN E1619 Submarine Propeller

The propeller used for the study is INSEAN E1619 generic submarine propeller. The propeller is a seven-bladed highly skewed submarine propeller with an unloaded tip blade design and the main particulars of the E1619 submarine propeller are given in Table 1 (Di Felice et. al. 2009). This propeller has been analyzed in self-propelling DARPA Suboff AFF8 condition and four quadrant conditions. Open water experiments were performed in the INSEAN towing tank, and wake velocity measurements were carried out by a Laser Doppler Velocimetry (LDV) system in the large circulating water channel at INSEAN. Results were presented by Di Felice et al. (2009). The main particulars of the E1619 submarine propeller are given in Table 1 and 3-D views are shown in Figure 1. In Figure 2 the detailed fine mesh used for the study is also presented.

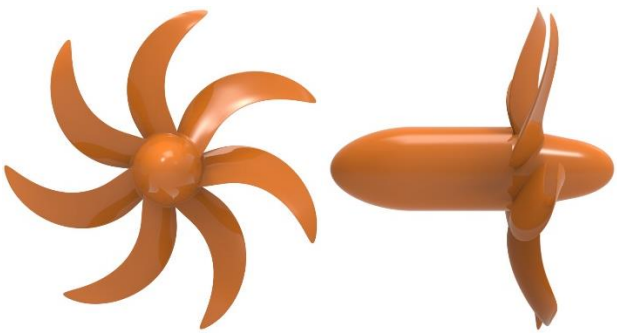

Figure 1 3-D views of INSEAN E1619 propeller

2.2 DARPA Suboff

DARPA Suboff AFF8 is a generic submarine model geometry with a length of 4.36 m comprising of 1.02 m fore-body, 2.23 m mid-body and 1.11 m aft-body. It has a cylindrical cross-section with a maximum diameter of 0.508 m. The AFF8 has a sail which is located at the top dead center of the hull starting at x = 0.92 m from the bow and ending at x = 1.29 m. It has a cross shaped rudder where rudders and hydroplanes are located at x=4 m from the bow. The hull and appendage arrangement of DARPA Suboff AFF8 is shown in Figure 3 and the main particulars are given in Table 2 (Liu and Huang, 1998). Views of the Figure 4 and Figure 5, respectively.

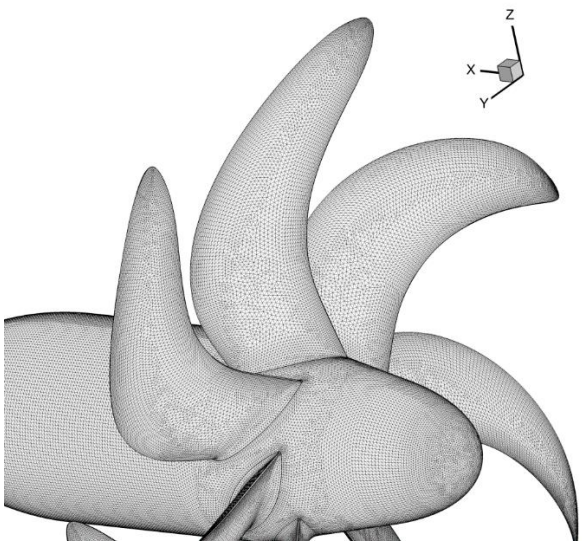

Figure 2 Detailed fine mesh for INSEAN E1619

Table 1 Main particulars of INSEAN E1619 submarine propeller (Di Felice et al., 2009)

Propeller Type	INSEAN E1619
Advanced Speed	1.68 m/s
RPM	280 RPM
Diameter	0.485 m
Number of Blades	7
A_E/A_0	0.608
Hub/Diameter Ratio	0.226
Pitch/Diameter ratio, P/D at 0.7 R	1.15

Figure 3 Geometry of DARPA Suboff AFF8 with E1619 Propeller fitted

Table 2 Main particulars of DARPA Suboff AFF8 (Liu and Huang, 1998)

Description	Symbol	Magnitude
Length overall	L_{oa}	4.356 m
Length between perpendiculars	L_{pp}	4.261m
Maximum hull radius	R_{max}	0.254 m
Centre of buoyancy (aft of nose)	FB	0.4621 L_{oa}
Volume of displacement	∇	0.718 m^3
Wetted Surface	S_{wa}	6.338 m^2
Propeller Diameter	P_D	0.262m

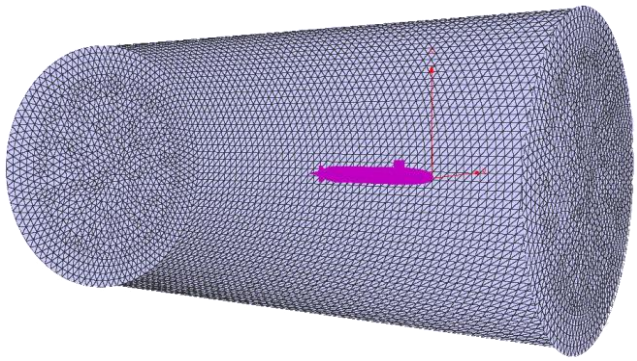

Figure 4 Calculation domain of DARPA Suboff

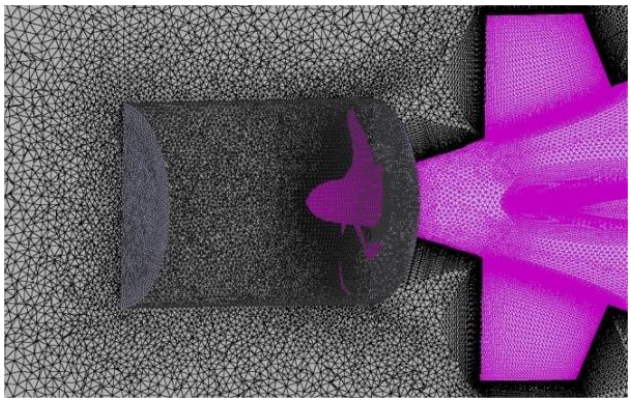

Figure 5 Cut-away view of DARPA Suboff

3 METHODOLOGY

Methodologies for calculation of propeller hydrodynamic performance, determination of self propulsion point and preparation of four quadrant propeller data are discussed in this section.

3.1 Methodology for Numerical Methods

3.1.1 Numerical Methods and Flow Solver

For the numerical calculations ANSYS 15 Fluent was used to satisfy the following governing equation for continuity Alin et. al. (2010);

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = 0 \qquad (1)$$

where x_i and v_i are the tensor form of axial coordinates and velocities, respectively. Then the momentum equation becomes

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial(\rho u_i v_i)}{\partial x_i} = -\frac{\partial \rho}{\partial x_i} + \frac{\partial \rho}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho \overline{u_i' u_j'}\right) \qquad (2)$$

where δ_{ij} is Kronecker Delta and $\rho\overline{u_i' u_j'}$ are the unknown Reynolds stresses.

For the turbulence modeling, SST k-ω turbulence model is employed due to its good performance on wall bounded boundary layer flows (Li, 2006).

FLUENT employs the cell-centered finite volume method. RANS formulation is used with absolute velocity selection. The transient solution is performed with a second order implicit pressure based solver. Velocity and pressure are coupled via the SIMPLE algorithm. Green Gauss Node Based is used for gradient and Pressure Staggering Option (PRESTO) for pressure discretization. Quadratic Upstream Interpolation for Convective Kinematics (QUICK) scheme was employed for Momentum, Turbulent Kinetic Energy and Specific Dissipation Rate calculations.

3.1.2 Determination of Self Propulsion Condition

Self-propulsion points of forward and astern speeds investigated numerically. For forward speed condition, max speed has been selected as 3.3436 m/s and initial values for numerical self-propulsion point investigation is calculated using the open water diagram of E1619 propeller. For backward speed condition it is assumed that DARPA Suboff is a 1/24 model of a 104.55 m long submarine which has a 7 knots of astern speed which is Froude scaled to 0.735 m/s for 4.356 m model.

At first, an arbitrary point for the self propulsion is selected by using resistance and openwater data. Than a greater and a smaller value for the rotational rate are selected for the numerical investigation. Than the results are plotted as it is shown on Figure 6 for forward speed and Figure 7 for speed astern. The intersection of the resistance and thrust lines gives the first point of interest. By using the thrust and resistance results for the third computation at this points turn the thrust and resistance lines into curves and the second intersection point is further investigated because it is very close to the self-propulsion point. Thus the self-propulsion point is located for the interested condition.

Table 3 Scaled full scale ship parameters for the assumption of astern speed

	Model		Full Scale	
Exp. Speed	6.5 kn	3.344 m/s	31.84 kn	16.38 m/s
Astrn. Speed	1.429 kn	0.735 m/s	7 kn	3.60 m/s
LOA	14.292 ft	4.356 m	343.0 ft	104.55 m

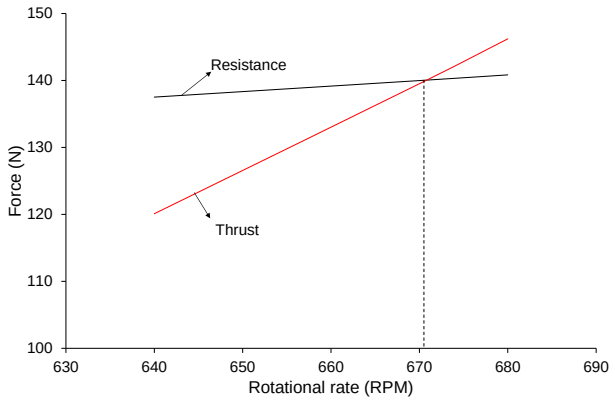

Figure 6 Self propulsion convergence graph for forward speed

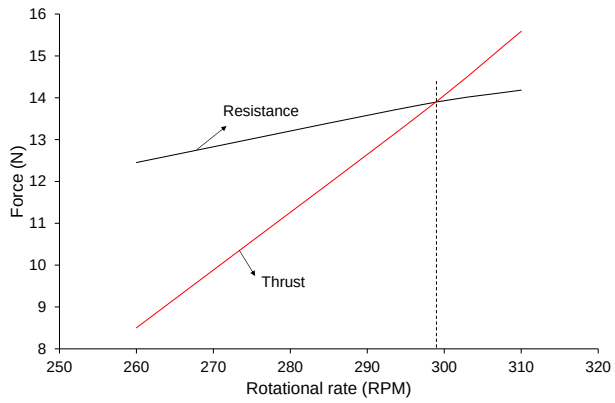

Figure 7 Self propulsion convergence graph for astern speed

3.1.3 Four Quadrant Data Preparation

DARPA Suboff and E1619 generic submarine-propeller assembly is widely used together so it is decided to arrange four quadrant conditions for E1619 propeller as it propels the Suboff AFF-8 geometry. For the calculation of β values different methods for the selection of advance speed and rotational rates investigated and it is decided to choose the values such that they cover the following essential conditions;

- Self-Propulsion point (SPP) at maximum forward speed (V_{fwdmax})
- Self-Propulsion point (SPP) at maximum backward speed (V_{bckmax})
- Crash-back maneuver
- Crash-forward maneuver

By the methodology described in previous section, self-propulsion points for forward and astern conditions are set as the reference points for propeller rate of rotation and flow speeds. In order to determine the off–design conditions for the propeller, hydrodynamic pitch angle, β, is defined instead of advance coefficient, J.

$$\beta = \arctan\left(\frac{V_A}{0.7\pi nD}\right) \tag{3}$$

In the cases where the flow speed is negative, it is assumed that the flow speed is equal to advance speed because the propeller is facing the flow. On the other hand, for positive flows, wake fraction, w, of DARPA Suboff model is evaluated using the open water curve and self-propulsion data and V_A is calculated with the formula:

$$V_A = V(1-w) \tag{4}$$

For the first quadrant, a forward constant rotational rate is computed for the linearly increasing forward speed until the β_{Q1} where the self-propulsion point for the first quadrant. Then it is followed by constant flow speed and decreasing rotational rate of the propeller until 0 speed where beta is 90°.

For the second quadrant, a constant flow speed is maintained until β_{Q2} where the crash-back maneuver occurs. Then the rate of rotation kept constant with decreasing flow speed until 0 where beta becomes 180°.

For the third quadrant, a constant rate of rotation and decreasing flow speed is maintained until the self-propulsion point at maximum astern speed where beta equals β_{Q3}. Then the flow speed is kept constant where propeller RPM decreasing and becomes 0 where β equals 270 °.

For the fourth quadrant, an increasing rate of rotation and a constant flow speed is maintained until β_{Q4} where the crash-ahead maneuver occurs. Then a constant propeller RPM and slowing the flow speed until beta equals 360 °.

3.2 Validation of Methodology

Open water performance calculations of E1619 propeller was carried out at J = 0.74 and J = 0.85. A cylindrical computation domain has been generated similar to the validation case. A mesh independence study was performed from coarse to fine meshes, using 6.386.638, 8.065.679 and 10.513.205 cells, respectively with non-dimensional wall distance value of $y^+ \approx 50$.

The convergence of grid study can be seen in Figure 8 with the above grid properties in comparison with the experimental values for thrust and torque coefficients at

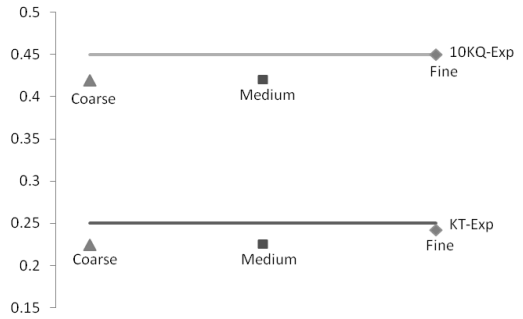

Figure 8 Comparison of convergence of CFD values and experiment results from coarse to fine mesh

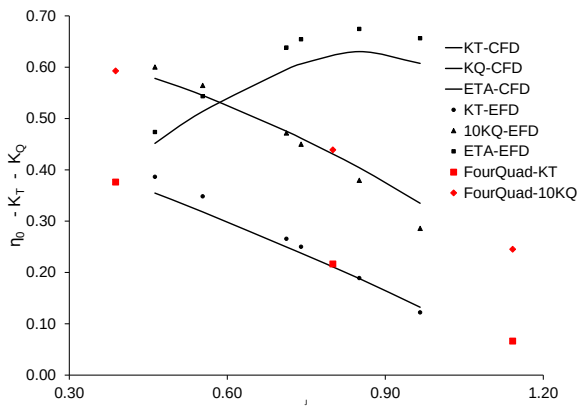

Figure 9 Comparison of open water characteristics calculation for E1619 with experimental results by Di Felice et al. (2009)

J = 0.74. During the experiments, the average blade Reynolds number, based on the section at 0.7 R, was about 2.3×10^5 (Di Felice et. al., 2009).

The results of the fine mesh are presented in Figure 9, indicating that RANS calculations captured the thrust, torque and open water efficiency values very well at the given advanced ratios.

4 COMPUTATIONAL PROCEDURE AND CONDITIONS

Self propulsion points for ahead and astern conditions are computed. Propeller shaft rotational speeds and flow speeds are determined and critical β values (β_{Q1}, β_{Q2}, β_{Q3}, β_{Q4}) are calculated. Variations of computational conditions are listed in Table4 and graphical distribution of speed and rates are presented in Figure 10.

Table 4 Four quadrant computational conditions for propeller rate of rotation and advance speeds

Quad	Advance Speed	Shaft Rotational Rate	β range
1st	+	+	0-90°
	0 to V_{fwdmax}	SPP at V_{fwdmax}	0 to β_{Q1}
	V_{fwdmax}	SPP at V_{fwdmax} to 0	β_{Q1} to 90°
2nd	-	+	90-180°
	V_{fwdmax}	0 to SPP at V_{bckmax}	90° to β_{Q2}
	V_{fwdmax} to 0	SPP at V_{bckmax}	β_{Q2} to 180 °
3rd	+	-	180-270°
	0 to V_{bckmax}	SPP at V_{bckmax}	180° to β_{Q3}
	V_{bckmax}	SPP at V_{bckmax} to 0	β_{Q3} to 270°
4th	-	-	270-360°
	V_{bckmax}	0 to SPP at V_{bckmax}	270° to β_{Q4}
	V_{bckmax} to 0	SPP at V_{bckmax}	β_{Q4} to 360°

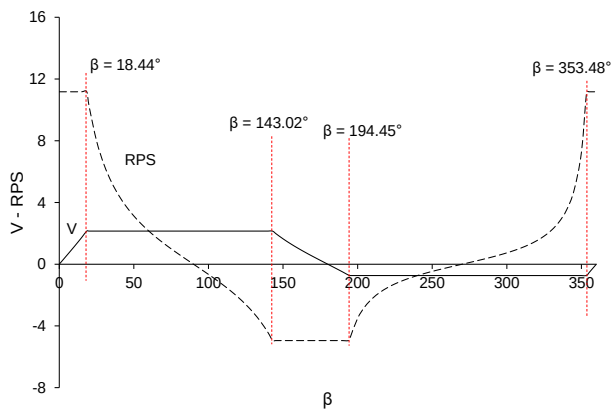

Figure 10 Four quadrant computational conditions for propeller rate of rotation and advance speeds

Computations are performed in order to determine thrust and torque values at every 10 degrees and at critical β values.

Calculated propeller thrust and torque are normalized to the relative velocity at 0.7 R radius defined as V_r, propeller thrust coefficient is defined by C_T and torque coefficient by C_Q.

$$V_r = \sqrt{V_a^2 + (0.7\pi n D)^2} \tag{5}$$

$$C_T = \frac{T}{\left(\frac{1}{2}\rho V_r^2\right)\frac{\pi}{4}D^2} \tag{6}$$

$$C_Q = \frac{Q}{\left(\frac{1}{2}\rho V_r^2\right)\frac{\pi}{4}D^3} \tag{7}$$

5 RESULTS

Four quadrant propulsion data for the INSEAN E1619 is presented graphically in Figure 11 where change of thrust coefficient (C_T) and torque coefficient (C_Q) over hydrodynamic pitch angle (β) can be seen.

Furthermore, propeller thrust and torque coefficients have been fitted with following Fourier series and Fourier coefficient of 30 harmonics are presented in Table 5.

$$C_T = \frac{1}{100}\sum_{k=0}^{30}\left[A_T(k)\cos(k\beta) + B_T(k)\sin(k\beta)\right] \tag{6}$$

$$C_Q = \frac{1}{1000}\sum_{k=0}^{30}\left[A_Q(k)\cos(k\beta) + B_Q(k)\sin(k\beta)\right] \tag{7}$$

6 CONCLUSION AND FUTURE WORKS

DARPA (Defence Advanced Research Projects Agency) Suboff submarine and INSEAN (Istituto Nazionale per Studi ed Esperienze di Architettura Navale) E1619 generic submarine propeller are widely used for numerical studies of submarine propulsion for forward speed. As an input for ship maneuvering simulations, it is necessary to know the propeller thrust and torque characteristics over the entire region of propeller operations. In order to compute the off-design characteristics of the propeller, a number of computations are performed for E1619 including validation of methodology in accordance with open water curve validation and mesh independence study. Suboff computations covered resistance analysis and self-propulsion analysis propelling both ahead and astern. In combination with the listed computations, critical hydrodynamic pitch angle (β) values are determined with a sensitivity of the propellers actual design conditions which covers the most important points of interest such as crash-back, crash-ahead, self-propulsion points ahead and astern. Change of thrust and torque coefficients over four quadrants is plotted and 30 harmonics of Fourier coefficients propeller data were presented.

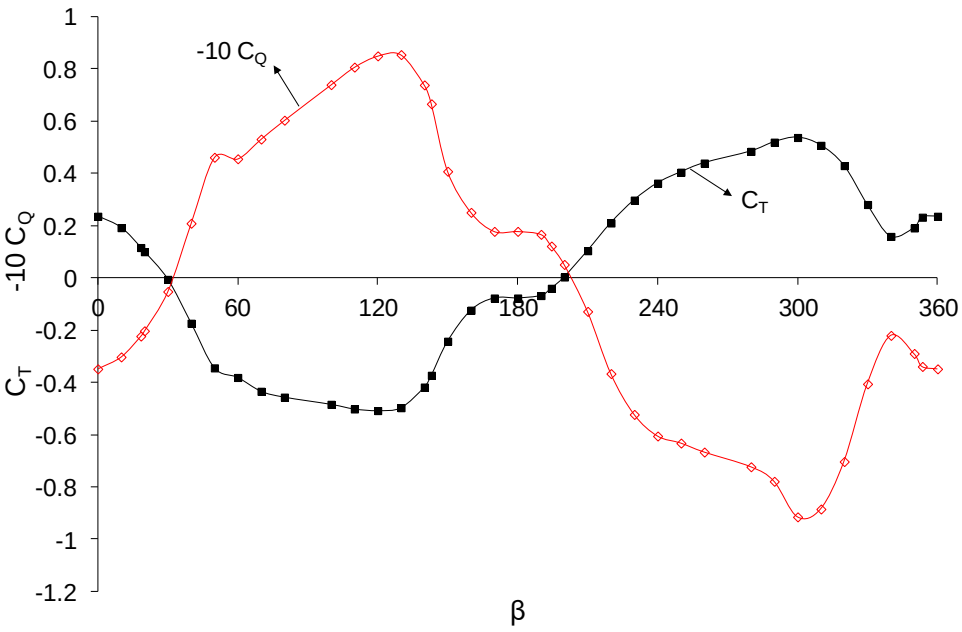

Figure 11 Variation of C_T and -10 C_Q values versus β

Table 4 Four quadrant computational conditions for propeller rate of rotation and advance speeds

Harmonic	A_T	B_T	A_Q	B_Q	Harmonic	A_T	B_T	A_Q	B_Q
0	1.498424	0.000000	-2.891878	0.000000	*16*	0.000000	-0.290927	0.000000	0.705674
1	13.119199	-47.024829	-24.704351	71.041666	*17*	0.000000	0.095153	0.000000	-1.293631
2	3.965658	-0.058344	-3.392882	-3.819588	*18*	0.374806	0.000000	-0.866563	0.000000
3	-0.451472	4.183603	3.067270	-3.988949	*19*	0.080186	0.000000	-0.363159	0.000000
4	0.799230	1.408274	1.085335	-0.872521	*20*	-0.813072	0.000000	1.917081	0.000000
5	0.305591	6.893388	-1.144907	-14.432598	*21*	0.000000	0.119419	0.000000	-0.811786
6	0.916856	0.225830	-2.754798	-0.920099	*22*	0.000000	-2.137151	0.000000	4.072457
7	0.000000	1.376007	0.000000	-1.723751	*23*	-0.111854	0.000000	0.194480	0.000000
8	0.000000	-0.440064	0.000000	1.254229	*24*	0.020584	0.000000	0.087521	0.000000
9	0.938343	0.000000	-0.871123	0.000000	*25*	-0.037882	0.000000	-0.016259	0.000000
10	1.241147	0.000000	-1.799467	0.000000	*26*	0.000000	0.251214	0.000000	-0.505316
11	0.728069	-0.642552	-0.750625	1.993276	*27*	0.000000	0.324032	0.000000	-1.361110
12	0.000000	-0.028226	0.000000	-0.259528	*28*	-0.603389	0.000000	1.232340	0.000000
13	0.000000	0.340156	0.000000	-1.468574	*29*	1.376813	0.000000	-2.478931	0.000000
14	0.525060	-2.159211	-1.145085	4.541591	*30*	0.000000	0.000000	0.000000	0.000000
15	-0.293625	0.000000	0.755236	0.000000					

Three future scopes of this work are:

- A new large cavitation tunnel may be established at İTÜ Ata Nutku Ship Model Laboratory in the near future and by this facility, four quadrant data can be measured experimentally.
- By using the produced four quadrant propeller properties, starting with Surge motion, DARPA Suboff's maneuvering motion can be simulated numerically.
- A free running model may be used for the validation of #2.

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