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Numerical Investigation of Submarine Tail Form on the Hull Efficiency

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ABSTRACT
One of the major parameters on determining the propulsion factors of submarines is the tail cone angle. This study is focused on the computational investigation of the effect of the change on tail cone angle and its influence on the hull efficiency. Numerical calculations are made by the Computational Fluid Dynamics code ANSYS Fluent. The investigation is carried out with the seven bladed submarine propeller model INSEAN E1619 and the generic submarine model DARPA Suboff which are extensively utilized in submarine validation studies. The DARPA Suboff geometry is reproduced according to different tail cone angles for constant displacement by the mathematical formulation of the submarine model. The validation of the numerical method is made for propeller open water characteristics and submarine resistance characteristics with data from open litterature. The self-propulsion point of the DARPA Suboff AFF8 configuration propelled with E1619 propeller is determined with numerical methods. After the validation of the numerical method with experimental results the resistance and propulsion characteristics of the generated geometries are analyzed with CFD. The propeller-hull interaction for different tail cone angles is investigated and compared by means of thrust deduction fraction, Taylor wake coefficient and hull efficiency.

Keywords
Submarine, wake, thrust deduction, hull efficiency, DARPA Suboff, E1619.

1 INTRODUCTION

Most significative factors in submarine propulsive performance are the submarine shape and the efficiency of its propulsion system. The efficiency of a propulsor and its accoustic performance depends mostly on the characteristics of the incoming flow which depends on the submarine form especially the tail shape; the tail cone angle, the sail's and appendage's shape and dimension (Renilson, 2015). Two factors are considered when a propulsion system is designed; the performance of the system and the effects caused by the interaction with the hull. These effects are the wake coefficient, thrust deduction factor and frictional losses. An approximate estimation of these values are very important in the preliminary design of a submarine.

The propeller characteristics behind the hull show difference to open water characteristics due to the incoming non-uniform flow. Therefore it is important to investigate the propeller-hull interaction. The studies in open litterature where RANS codes are used for modelling the propeller-hull interaction can be seperated depending the used propeller model as studies using the viscous or inviscid approach (Tokgöz 2015). The inviscid model is firstly used by Stern et al (1988) where the propeller is prescribed as a body-force model based on an actuator disk approach, many researchers carried out the same approach like Piquet (1987), Dai et al (1991), Hally and Laurens (1998), Chen and Lee (2004). Some of the pioneering studies where the viscous approach is used are Sreenivas et al (2003), Lübke (2005), Potanza and Chen (2006) and Carrica et al (2012). The viscous method offers an effective approach for the detailed propeller performance prediction besides the requirements for grid generation and computational power are much larger than the inviscid method.

In open litterature the DARPA Suboff submarine model propelled with the E1619 propeller is extensively used. Alin et al (2010a) investigated the flow around the DARPA Suboff submarine with DES and LES methods. The aim of the study was to compare the effects of different flow simulation methods on the flow around submarines. Again in 2010 Alin et al (2010b) investigated the propeller/hull interaction of submarines. In this study they investigated the acoustics caused by the flow around the fully appended DARPA Suboff and a surface vessel with LES. Liefvendahl & Troeng (2011) investigated with LES the cycle to cycle propeller loading of a submarine propeller. Nathan Chase (2012, 2013) simulated in CFDShip-Iowa V4.5 the flow around DARPA Suboff propelled with E1619 propeller.

The effects of the tail cone angle on the hull efficiency is presented in open literature in Burcher & Rydill (1994), Kormilitsin & Khalizev (2001) and Lee et al (2003). The results presented by Burcher & Rydill and Kormilitsin&Khalizev differ greatly for the same tail cone angles. So in this study the fully appended DARPA

Suboff submarine model propelled with E1619 propeller is investigated for different tail cone angles by means of hull efficiency, Taylor wake coefficient and thrust deduction factor. Firstly the propeller open water characteristics and the resistance characteristics of the submarine are obtained by a CFD code ANSYS FLUENT and the method is validated with experimental results from open literature. Than the tail form of the submarine is derived for different tail cone angles for constant displacement. The original model with propeller and the derived geometries are investigated by CFD and the self-propulsion points are obtained by the load varying self-propulsion test method. Finally the results are presented by means of Taylor wake coefficient, thrust deduction factor and hull efficiency.

2 GEOMETRIES

2.1 DARPA Suboff

DARPA Suboff AFF8 is a generic submarine model geometry with a length of 4.36m and a maximum diameter of 0.508m. It has a cylindrical cross-section and the sail is located at the top dead center of the hull starting at x=0.92m from the bow and ending at x=1.29m. It has a cross shaped rudder where rudders and hydroplanes are located at x=4m from the bow. The hull and appendage arrangement is shown in Figure 1 and the main particulars are given in Table 1 (Groves et al, 1998).

Figure 1. Geometry of DARPA Suboff AFF8

Table 1. Main Particulars of DARPA Suboff

Generic Submarine Type	DARPA Suboff AFF8	
Description	**Symbol**	**Magnitude**
Length overall	L_{OA}	4.356 m
Length between perpendiculars	L_{PP}	4.261 m
Maximum hull radius	R_{MAX}	0.254 m
Centre of buoyancy (aft of nose)	LCB	0.4621 Loa
Volume of displacement	∇	0.718
Wetted Surface Area	S_{WA}	6.338

2.2 E1619 Propeller

The INSEAN E1619 generic submarine propeller is a seven-bladed highly skewed propeller with an unloaded tip blade design (Figure 2). The main particulars of the E1619 submarine propeller are given in Table 2. The open water characteristics are performed in the towing tank of INSEAN and the wake velocity measurements in the large circulating water channel (Di Felice et al 2009).

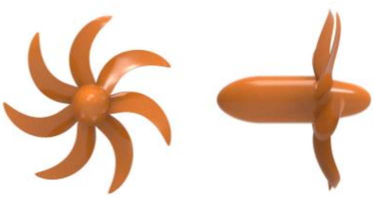

Figure 2. E1619 propeller

Table 2. Main particulars of INSEAN E1619

Propeller type	INSEAN E1619
Advance speed	1.68 m/s
RPM	280 rpm
Diameter	0.485 m
Number of blades	7
AE/AO	0.608
Hub/Diameter ratio	0.226
Pitch to diameter ratio, P/D at 0.7R	1.15

2.3 DARPA Suboff Derived for Different Tail Cone Angles

The tail cone angle of a submarine is used to describe the inclination in the aft. It defines generally the maximum inclination angle and is measured by a tangent line beginning from the propeller hub to the hull. The geometry of DARPA Suboff is described with mathematical formulations for the bow, parallel midbody, aft geometry and appendages (Groves et al, 1998). The mathematical formulation for the aft geometry is defined as below:

Aft perpendicular begining from x=13.979167 ft

10.645833 $\leq$ x $\leq$13.979167 ft

$$R = R_{MAX}\left\{r_h^2 + r_h K_0 \ell^2 + \left(20 - 20r_h^2 - 4r_h K_0 - \frac{1}{3}K_1\right)\mathcal{E}^3 + (-45 + 45r_h^2 + 6r_h K_0 + K_1)\mathcal{E}^4 + (36 - 36r_h^2 - 4r_h K_0 - K_1)\mathcal{E}^5 + \left(-10 + 10r_h^2 + r_h K_0 + \frac{1}{3}K_1\right)\mathcal{E}^6\right\}^{1/2} \quad (1)$$

$$\mathcal{E} = \frac{13.979167 - x}{3.333333}, x\ (feet) \quad (2)$$

R_{MAX}=0.8333 feet and r_h=0.1175 are constants. For the original DARPA Suboff geometry the constants K_0 and K_1 are 10 and 44.6244 respectively. It is determined that the aft geometry can be modified by changing the constants K_0 and K_1. The tail cone geometry is modified from 12.5 to 22 degrees for constant displacement by varying the constants K_0 and K_1 (Figure 3). From the investigation it is observed that K_0 controls the slope of the curve and that K_1 could be used to shift the geometry in parallel and control the volume. A linear relation is obtained between K_0, K_1 and the half tail cone angle values (Figure 4). Among the investigated cases four significant cases where the half-tail cone angle is 16, 18, 20 and 22 have been selected for the study (Figure 5) (Table 3).

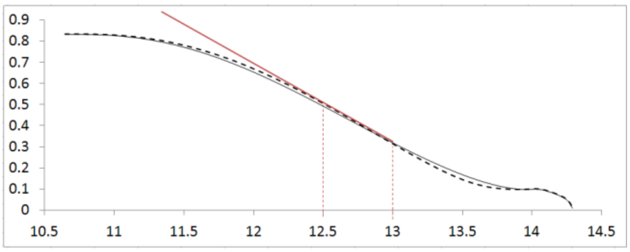

Figure 3. Measurement location of tail cone angle

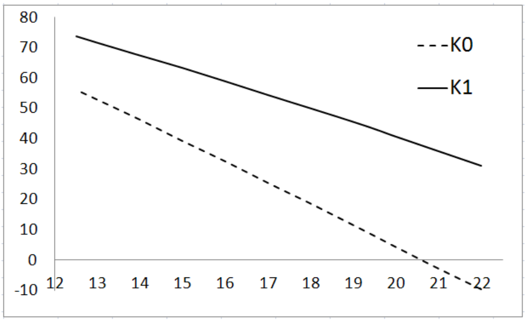

Figure 4. K_0 and K_1 values

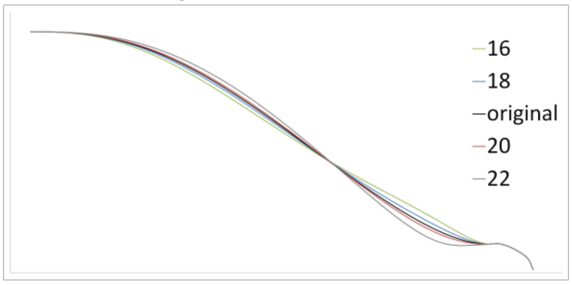

Figure 5. Selected geometries

Table 3. K_0 and K_1 values of the selected geometries

Half-tail cone angle	K_0	K_1
16	32.60	59.00
18	18.70	50.10
20	4.40	40.80
22	-9.50	31.20

3 NUMERICAL METHOD and VALIDATION STUDIES

The computational fluid dynamics calculations are made with the commercial finite volume code ANSYS Fluent 14.5. Steady RANS computations are performed in all calculations. The grid generation is made with unstructured mesh in Pointwise. T-REX elements are used to provide the non-dimensional wall distance y^+=50. The mesh independence study of the propeller model is made for three different mesh densities by varying the medium mesh with the factor $\sqrt[3]{2}$. The SST (Shear Stress Transport) k-ω turbulence model is used in the calculations. The turbulence intensity and viscosity ratio is selected in the boundary conditions. The solution scheme is selected as SIMPLE (Semi Implicit Methods for Pressure Linked Equations) and the gradient discretisation is Green-Gauss node based.

Table 4. Solution methods and turbulence boundary conditions

	E1619 Propeller	DARPA Suboff	DARPA Suboff with E1619
Pressure Gradient	PRESTO	Second order	Second order
Momentum Gradient	QUICK	Second order	Second order
Turbulent Kinetic Energy	QUICK	QUICK	QUICK
Specific Dissipation Rate	QUICK	QUICK	QUICK
Turbulent Intensity (%)	2.5	2	2
Turbulent Viscosity Ratio	10	5	5

3.1 Validation of E1619 Propeller

A cylindrical computational domain with the length -6.2<x/D<3.09 and diameter r/D<6.2 is generated for the CFD calculations (Figure 6). The propeller is placed in a Chimera block with the length of 2.5D and diameter 1.5D to which the rotation motion is defined with the Moving Reference Frame option. The incoming flow is defined with velocity inlet for V=1.68 m/s as in the experiments conducted by Di Fellice et al. The flow velocity is kept constant and the propeller rate of rotation is changed for different advance speeds. The outflow is defined as pressure outlet and is accepted as zero. The propeller and the hub are defined as non-slip wall, the outer domain as symmetry and the inner domain as interface. The mesh independence study is made for three different mesh densities; $3.8x10^6$, $6.6x10^6$, $11.8x10^6$. The open water diagram obtained for different mesh densities is presented in Figure 8. For J=0.74 the K_T and K_Q values are predicted with %7 and %2 errors respectively for the dense mesh. For the medium and fine mesh the error values are %0.3, %0.4 for K_T and %6 for K_Q. The wake obtained for the medium and fine mesh in the location x=0.17R behind the propeller is compared with experimental results in Figure 9. The mesh for medium density is selected for further computations.

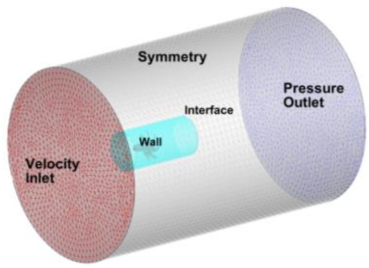

Figure 6. Computational domain of the E1619 Propeller

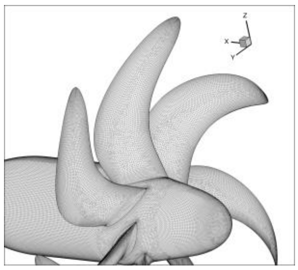

Figure 7. Medium mesh view of the propeller

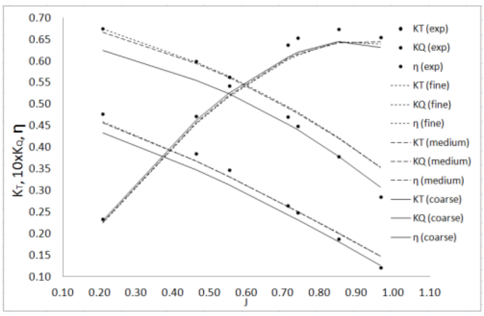

Figure 8. Open Water Diagram for E1619 Propeller

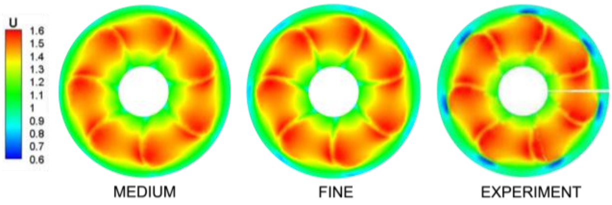

Figure 9. Wake behind E1619 propeller in x=0.17R for different mesh densities

3.2 Validation of DARPA Suboff Submarine Model

The Darpa Suboff submarine model is investigated in a cylindrical computational domain extending from -1.03<x/L< 3.78 in length and r/L<1.6 in diameter (Figure 10). The grid consists of $11x10^6$ elements (Figure 11). The incoming flow is defined with velocity inlet and the outflow is defined with pressure outlet. The submarine is defined as non-slip wall and the outer cylindrical domain is defined as symmetry. The results obtained by CFD are compared with experimental results from Liu&Huang (1998) and Crook (1990). The error rate of the numerical results with the experiments is for the range of the Reynolds number between $12x10^6$ - $18x10^6$ as %1 and for greater Reynolds number values %6 (Figure 12, Table 5). The nominal wake distribution is compared with experimental results in the location x/L 0.98, 1.04 and 1.20 (Figure 13, 14, 15). It is seen that the results are in good agreement by means of resistance and wake distribution. The medium mesh is selected for further calculations.

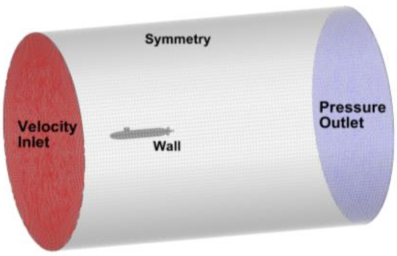

Figure 10. Boundary conditions

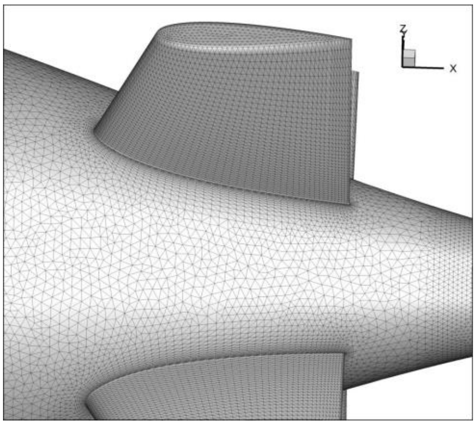

Figure 11. Mesh view

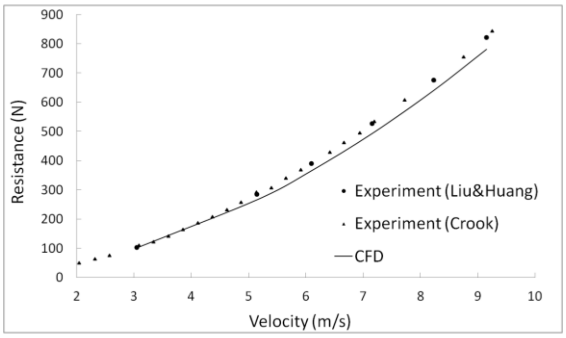

Figure 12. Resistance characteristics of DARPA Suboff

Table 5. Resistance values of DARPA Suboff

Reynolds Number	Velocity (m/s)	Experiment (Liu&Huang) Resistance (Newton)	CFD Resistance (Newton)	Error
$1.2x10^7$	3.050	102.3	101.27	0.010
$2.0 x10^7$	5.144	283.8	265.53	0.064
$2.4 x10^7$	6.096	389.2	364.86	0.063
$2.8 x10^7$	7.160	526.6	492.98	0.064
$3.2 x10^7$	8.230	675.6	639.87	0.053
$3.6 x10^7$	9.151	821.1	780.36	0.050

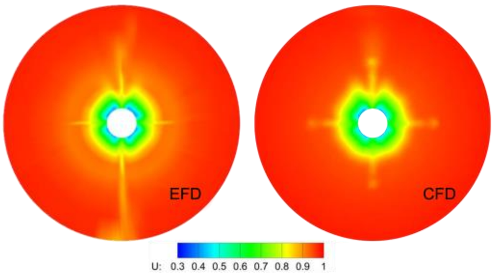

Figure 13. Wake distribution in x/L=0.98

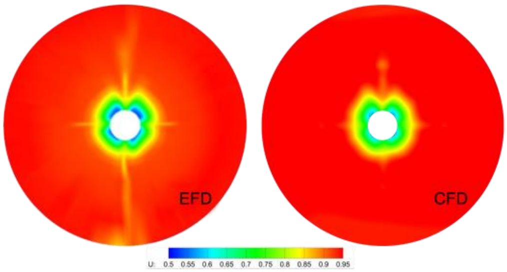

Figure 14. Wake distribution in x/L =1.04

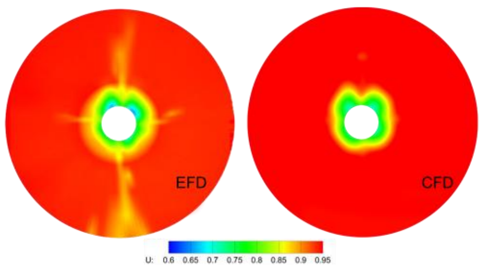

Figure 15. Wake distribution in x/L =1.20

4 DETERMINATION OF THE SELF-PROPOLSION POINT of DARPA SUBOFF

The self-propulsion point of the DARPA Suboff submarine propelled with E1619 propeller is determined according to the load varying self-propulsion test method. The mesh density is selected in accordance with the mesh independence study. The computational domain has the same dimension as the AFF8 configuration (Figure 15). The propeller behind the submarine is placed in a Chimera block which is 3D long and has a diameter of 1.5D (Figure 16). The moving motion is defined for the propeller with the moving reference frame option. The incoming flow is defined with velocity inlet and the outgoing flow is defined with pressure outlet boundary condition. The submarine hull and the propeller are defined as non-slip wall and the outer cylindrical surface as symmetry. The flow velocity is V=2.75 m/s. The propeller loading is changed to be bigger and smaller than the predicted self-propulsion point by changing the rate of revolution of the propeller. For both cases the intersection of the obtained results for thrust of the propeller and resistance of the submarine is determined as self-propulsion point (Figure 18). From the analyses carried out for this point the Taylor wake coefficient, thrust deduction fraction and hull efficiency is calculated (Table 5).

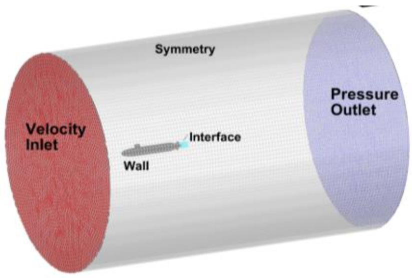

Figure 16. Boundary conditions

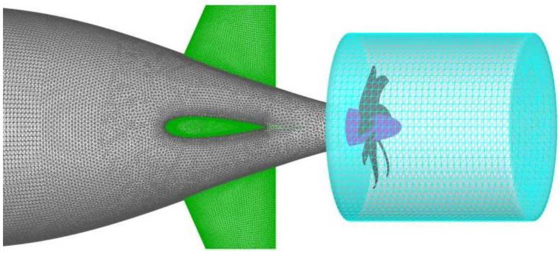

Figure 17. Mesh view

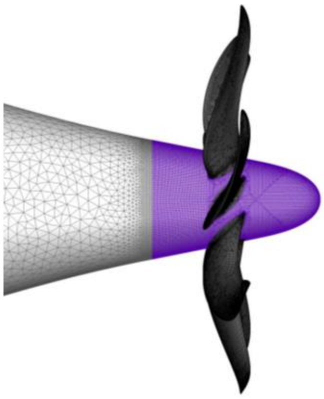

Figure 18. Mesh view

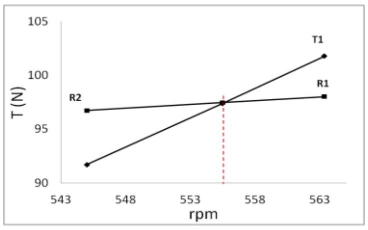

Figure 19. Determination of the self-propulsion point

Table 5. Results for the self-propulsion point

CASE	n (rpm)	T (N)	R (N)
1	563.3321	101.0934	97.7996
2	545.0000	91.0272	96.5209
Self-propulsion point	555.4800	97.4013	97.4577

The propeller rate determined for V=2.75 m/s is n=555.48 rpm. The advance coefficient for this speed is:

$$J_P = \frac{V_S}{nD} = 1.1337 \tag{3}$$

The predicted thrust force T=97.4013N and moment is Q=4.9034Nm. From these values the thrust coefficient and torque coefficient are calculated as below:

$$K_{TP} = \frac{T}{\rho n^2 D^4} = \frac{97.4013}{998.2 \times 9.2580^2 \times 0.262^4} = 0.2416 \tag{4}$$

$$K_{QP} = \frac{T}{\rho n^2 D^5} = \frac{97.4013}{998.2 \times 9.2580^2 \times 0.262^5} = 0.04643 \tag{5}$$

To obtain the propeller characteristics behind the submarine the thrust identity method is used. For this the predicted K_{TP} value obtained numerically is placed in the open water diagramm. From this value a straigt line is drawn to obtain the values for the advance coefficient (J_0), the torque coefficient (K_{Q0}) and the hull efficiency (η_0). Thus it is possible to obtain the open water charcteristics for the case equivalent to the flow velocity behind the submarine. The advance coefficient is determined as J_0=0.7280, the torque coefficient as K_{Q0}=0.0470 and the propeller efficiency as η_0=0.6030.

From these values the Taylor wake cfraction is;

$$w_T = \frac{J_P - J_0}{J_P} = \frac{1.1337 - 0.7280}{1.1337} = 0.3579 \tag{6}$$

The thrust deduction ;

$$t = \frac{T - R_m}{T} = \frac{97.4013 - 82.6032}{97.4013} = 0.1519 \tag{7}$$

And the hull efficiency;

$$\eta_H = \frac{1-t}{1-w_T} = \frac{1-0.1519}{1-0.3579} = 1.3207 \tag{8}$$

The relative rotative efficiency is defined as the rate of the torque coefficient obtained from propeller open water diagramm to the value behind the submarine and is calculated as below:

$$\eta_R = \frac{K_{QPo}}{K_{QP}} = \frac{0.044}{0.046} = 1.0125 \tag{9}$$

The propulsive efficiency is calculated as below:

$$\eta=\eta_0\eta_H\eta_R=0.6030\text{x}1.3207\text{x}1.0125=0.8064 \quad (10)$$

5 INVESTIGATION OF THE HULL EFFICIENCY FOR DIFFERENT TAIL CONE ANGLES

The propulsive characteristics of the derived geometries of DARPA Suboff propelled with the E1619 propeller are predicted with numerical methods as in Section 4. The velocity is V=2.75 m/s. The half-tail cone angle of the submarines are 16 (DKKA1), 18 (DKKA2), 20 (DKKA4) and 22 (DKKA5) degrees.

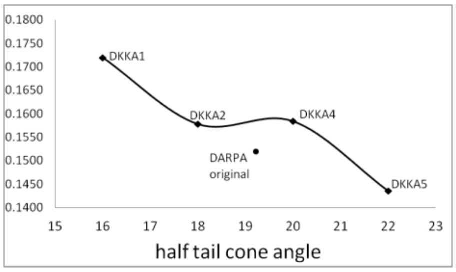

Figure 20. Trust deduction

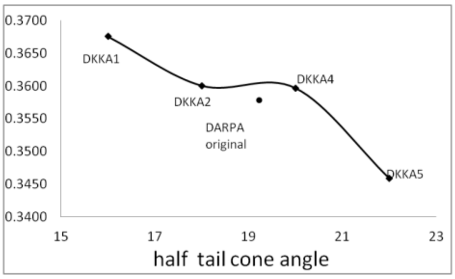

Figure 21. Taylor wake fraction

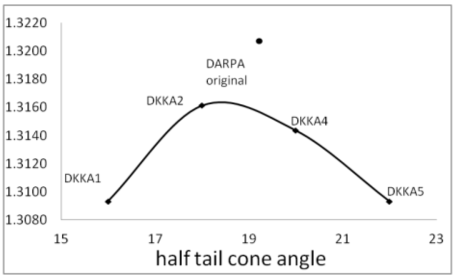

Figure 22. Hull efficiency

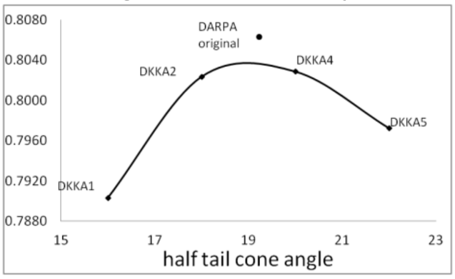

Figure 23. Propulsive efficiency

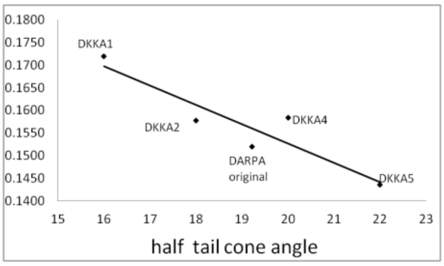

Figure 24. Trust deduction

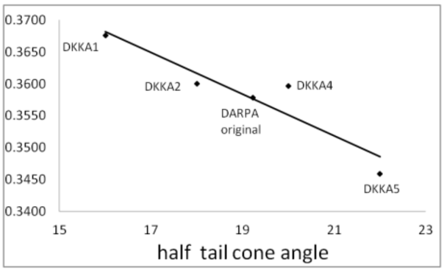

Figure 25. Taylor wake fraction

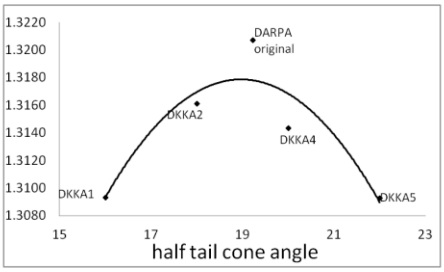

Figure 26. Hull efficiency

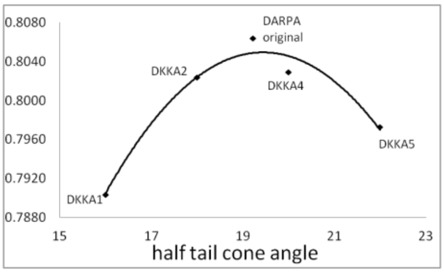

Figure 27. Propulsive efficiency

The thrust deduction, Taylor wake fraction, hull efficiency, relative rotative efficiency and propulsive efficiency are presented in accordance to the tail cone angle in Fig 20-27 and Table 6-7.

Table 6. Resistance and Propulsive characteristics

Case	**Angle**	**R (N)**	**T (N)**	**rpm**
DKKA_1	16	82.3200	99.7693	555.28
DKKA_2	18	82.6107	98.1817	555.32
DKKA_4	20	82.6311	98.1810	555.45
DKKA_5	22	82.8613	96.7473	556.70

Table 7. Propulsive characteristics

Case	t	w	η_H	η_R	η_D
DKKA_1	0.1749	0.3669	1.3033	1.0122	0.7902
DKKA_2	0.1586	0.3598	1.3143	1.0084	0.8019
DKKA_4	0.1584	0.3597	1.3144	1.0097	0.8029
DKKA_5	0.1435	0.3459	1.3093	1.0015	0.7973

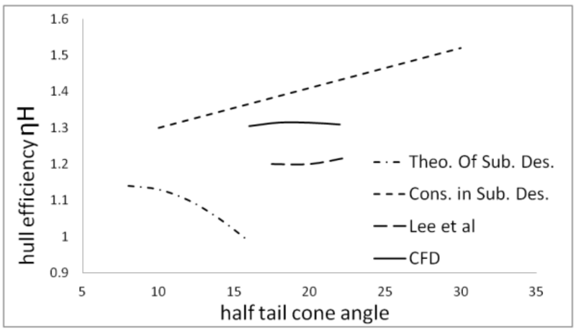

Figure 28. Comparison of hull efficiency for different tail cone angles

The change of thrust deduction, taylor wake fraction, hull efficiency and propulsive efficiency is given in Figure 20-22 for different tail cone angles in comparison with the original DARPA Suboff geometry. From Figure 24 to 27 the average values obtained with regression polynomials are presented. In Figure 28 the obtained hull efficiency values are compared with data from open litterature.

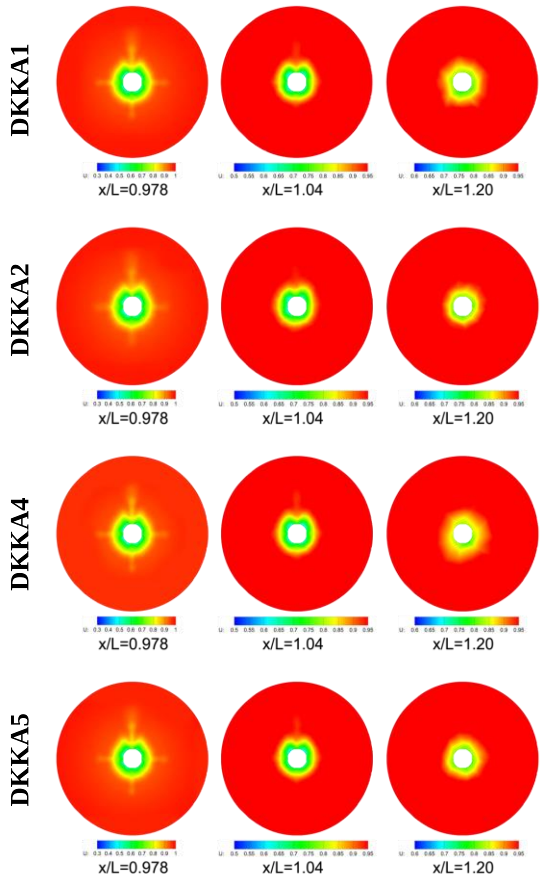

Figure 29. Nominal wake of DARPA Suboff for different tail cone angles

6 RESULTS

In this study the self-propulsion characteristics of the DARPA Suboff Submarine model propelled with INSEAN E1619 propeller is investigated with CFD for different tail cone angles. At first the validation study of the CFD method is made for the E1619 submarine propeller. A good accordance of the results is seen by means of propeller open water characteristics and wake velocities. Next the resistance characteristics of the DARPA Suboff Submarine AFF8 configuration are investigated and it is seen that the resistance and nominal wake characteristics are in good accordance with experimental results. The self-propulsion point of the DAPA Suboff model propelled with E1619 is carried out according the load varying self-propulsion test method and the thrust identity method. The thrust deduction, Taylor wake fraction, relative rotative efficiency, hull efficiency and propulsive efficiency are calculated. To investigate the effects of the tail cone angle the mathematical formulation for the aft part of the DARPA Suboff Submarine model is modified with the change of the K_0 and K_1 coefficients for constant displacement. Four geometries with different tail cone angles are generated. The resistance characteristics and propulsion characteristics with the E1619 propeller of the generated geometries are carried out by quasi-steady RANS method.

In 'Theory of Submarine Design' by Kormilitsin & Khalizev it is showed that by the increase of the tail cone angle; the thrust deduction increases, the Taylor wake fraction and the hull efficiency decreases. In 'Concets of Submarine Design' by Burcher & Rydill by the increase of the tail cone angle the thrust deduction increases, the Taylor wake fraction increases and the hull efficiency increases. In another study from Lee et al the thrust deduction increases, the Taylor wake fraction increases and the hull efficiency increases by the increase of the tail cone angle.

The results obtained from this study can be summarized as follows:

The propeller open water characteristics are obtained for medium and fine mesh within the error range of %0.3, %0.4 for K_T and %6 for K_Q. The wake velocities behind the propeller plane are very good predicted for J=0.74.

The resistance characteristics of the fully appended AFF8 configuration are very well predicted (%1) for smaller Reynolds numbers ($12x10^6$ - $18x10^6$) and in larger Reynolds numbers the error rate reaches %6. The nominal wake distribution in three different planes behind the submarine show very good accordance with experimental results. The effects of the struts during the experiment are not seen in CFD since only the submarine model is analyzed.

The self-propulsion points and propulsion characteristics of the original and derived geometries are obtained. A slightly increase of the resistance values is seen by the increase of the tail cone angle while the required thrust in the self-propulsion points increases. It is seen that the increase of the tail cone angle causes a decrease of the thrust deduction and Taylor wake fraction. The hull efficiency reaches its maximum near the tail cone angle of 19-20° which is the original geometries tail cone angle. So it can be concluded that for the DARPA Suboff Submarine the best hull efficiency is obtained for the range of 19-20°.

The suggestions given in the open literature about the submarine tail cone angle and the change of the hull efficiency contradict each other. No detailed information was available on whether the sources outside Lee et al found the results with experimental or computational methods. While Kormilitsin & Khalizev show that the hull efficiency decreases by the increase of the tail cone angle Burcher & Rydill show that the hull efficiency increases. The results obtained in this study show that there is neither a constant increase nor decrease of the values but there are some optimum values.

In next studies it is aimed to investigate another submarine hull form for the same tail cone angles.

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