Hydro-Acoustic and Hydrodynamic Optimization of Darpa Suboff Submarine Bow Form Using Genetic Algorithm

B. U. Yazici *
Istanbul Technical University, Istanbul, Turkey

As submarine underwater noise characteristics is the most important parameter to be considered in order to operate safely, it is very crucial to predict and control underwater noise levels of submarines. The main goal of this study is to enhance hydro-acoustics and hydrodynamics performance of Darpa Suboff submarine with bow form optimization using high-fidelity CFD solver and optimization algorithms. Flow around the benchmark Darpa Suboff has been solved using using Reynolds Average Navier-Stokes(RANS) method. Hydro-acoustics analysis have been performed using Unsteady Reynolds Average Navier-Stokes(uRANS) with Ffowcs-William and Hawkings (FW-H)equation. The analyses have been carried out by assuming 3-D, turbulent, incompressible and the governing equation have been discretized with finite volume method(FVM).

I. Nomenclature

$H(f)$	=	heaviside function
ρ	=	density
p'	=	far-field sound pressure
$\delta(f)$	=	dirac delta function
T_{ij}	=	lighthill tensor
ν	=	kinematic viscosity

II. Introduction

Submarine underwater radiated noise is a very crucial parameter for its the safe and stealth operation. The manifold origins of the submarine self-noise can be treated under three categories. **Propeller noise** is the noise which originates at the submarine's screws when the speed is great enough to produce propeller cavitation. **Hydrodynamic noise** includes all the noise sources which result from the motion of the submarine through water. **Machinery noise** is the noise resulting from the propulsion, maneuvering and auxiliary machinery of the submarine.

One of the most important studies that formed the basis of today's acoustic studies was carried out by Lighthill [1]. Based on Lighthill's work, Curle conducted a study about body and fluid interaction [2]. In 1969, a method developed by Ffowcs-Williams and Hawkings (FW-H) for calculation of noise of an arbitrary body moving in a fluid became one of the milestones of acoustic studies [3].

Recently, most researchers studying hydrodynamic noise treat the underwater vehicle as a rigid body[4, 5]. Yao et al. [6] investigated the flow-exites noise of submarine withfull appendages by considering FSI with the BEM. The flow field around the submarine is simulated by applying the large eddy simulation (LES). Moonesun et al. [7, 8]investigated optimum hydrodynamic shape of the submarine bow and stern.

In this study, Hydrodynamic noise will be evaluated using benchmark submarine geometry named as *Darpa Sub-off*. The reason why hydrodynamic noise has been chosen among aforementioned three categories is that hydrodnamic noise is the dominant noise source for the submarines in general. Hydrodynamic noise includes the turbulent pressures produced by flow vortices, the rattles and vibration induced by the flow in the submarine plating. Thus, although hydrodynamic noise has a variety of origins which depend on particular conditions, all are the results of the motion of the submarine through the water. Hydrodynamic noise has a sensibly continuous spectrum, in this respect it differs from most markedly from machinery noise which has a discontinuous spectrum containing line components.

*PhD Student, Senior Submarine Design Engineer, STM Savunma Teknolojileri Mühendislik ve Ticaret A.Ş. , Istanbul/bugur.yazici@gmail.com

Main reason behind is study is to develop an iterative design pattern to reduce noise levels that are generated by the hydrodynamic characteristics of the submarine using high-fidelity CFD solver and optimization algorithms. The design pattern has an objective to reduce both underwater radiated noise and hydrodynamic resistance values of the Darpa Sub-off geometry. Main particulars of the geometry and outlook of the vessel can be found in Section IV Table 1 and Fig 2, respectively.

CAESES-Friendship software has been utilized to create parametric submarine hull form and to integrate high-fidelity solvers with the optimization algorithms that are shipped with the CAESES. Bow form of the Darpa Sub-off has been parameterized using following equation which creates an axisymmetric curve:

$$r_{x_f} = \frac{D}{2}\left[1 - \left(\frac{x_f}{L_F}\right)^{n_f}\right]^{\frac{1}{n_f}} \tag{1}$$

Parameters of the equation (1) can be indicated as follows:

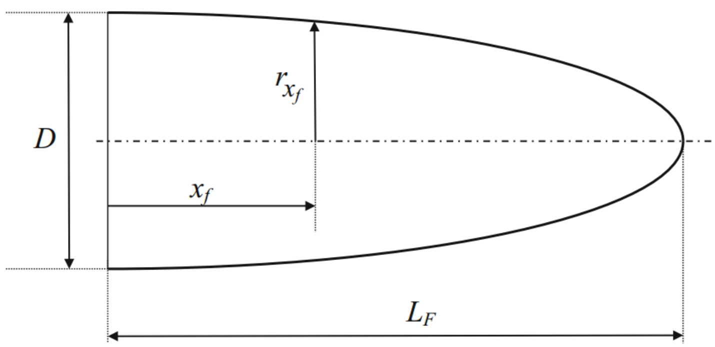

Fig. 1 Axisymmetrical Bow Form Parameters.

Using parameters in equation (1), multi-objective/constrained optimization problem can be defined mathematically as follows:

$$\begin{aligned} \text{Objective Function : } & min(0.5 * F_1() + 0.5 * F_2()) \\ \text{Subject to :} & g_1(s) = 0.75 < L_F < 1.15 \\ & g_2(s) = 1 \leq n_F \leq 5.5 \\ & h_1(s) = D = B_{Darpa} \end{aligned} \tag{2}$$

Where:

$F_1()$	=	Total resistance value including pressure and shear stresses
$F_2()$	=	Acoustic OASPL value measured from 1 meter behind the propeller hub of the Darpa Sub-off geometry
$g_1(s), g_2(s)$	=	Inequality constraints
$h_1(s)$	=	Equality constraint
L_F	=	Maximum distance between the start point and end point of the axisymmetric curve
n_F	=	Fulness coefficient of the parametric form
B_{Darpa}	=	Maximum breadth of the Darpa Sub-off geometry

In this study, SOBOL algorithm will be used to determine the design parameters for the optimization process. High fidelity commerical CFD Solver Star-CCM+ will be utilized to solve u-RANS and Ffowcs-William and Hawkings equations. SOBOL methodology has been chosen to obtain equally scattered parameters defined in the equation (2). Since the computation costs of the aforementioned CFD equations are highly expensive, it has been also decided to see the results of the intermediate points rather than the number of samples entered in SOBOL phase. A surrogate model will be created by using the results obtained in SOBOL simulations. The high fidelity model of the optimization variables during the iterations will be created and implemented as input values for a surrogate model. LinearNDInterpolator

Table 1 Initial parameters of parametric bow form

n_f	2.35
L_F	0.92445413

method from well-known open-source python library is used to generate the surrogate model and NSGA-II algorithm will be implemented to solve objective function in equation(2).

Approximate initial bow form of the Darpa Sub-off will be the starting point of both SOBOL and NSGA-II algorithms. In order to achieve approximate bow form that is very close to the original bow form, following parameter values will be used to create axisymmetrical curve.

Created parametric curve using above values is shown in red and the original curves are in black in Figure 2.

Fig. 2 Comparison of the original and parametric curve.

As mentioned earlier, SOBOL and NSGA-II algorithms are shipped with CAESES-friendship software. However, in order to implement LinearNDInterpolator and make it available for the usage of the NSGA-II in the further optimization steps, scripts were developed using Python programming language. After that, the protocols between CAESES and python code should be done since CAESES will use the output of the python code that includes LinearNDInterpolator implementation.

III. Theoretical Background

The resistance and hydro-acoustics analyses of the submarine have been solved with state-of-art commercial code Star CCM+ using RANS and uRANS solver, respectively. $SST k - \omega$ turbulence model is applied in order to simulate the turbulent flow around the submarine. Second order-upwind scheme has been selected for the momentum and turbulence terms and the SIMPLE algorithm for velocity pressure interaction has been selected. Time dependent pressure data is used as the input for the FW-H equation to predict far-field acoustics.

A. Numerical Method and Flow Solver

The governing equations are the continuity and the uRANS equations for the time dependent, three-dimensional, incompressible flow;

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = 0 \tag{3}$$

is the continuity,

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_i j\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \quad (4)$$

is the momentum equation where x_i and v_i expresses the tensor form of axial coordinates and velocities, respectively, $\delta_i j$ is Kronecker Delta, ρ is the density, v is the kinematic viscosity of fluid and $-\rho\overline{u_i' u_j'}$ are the unknown Reynolds stresses.

For the turbulence modeling , $k - \omega$ turbulence is used to simulate turbulent flows. Further detail for the $k - \omega$ turbulence model can be found in [9]

B. Ffowcs-William and Hawkings Method

For the acoustics analysis of the submarine the integral equation FW-H is solved to find the far-field sound of the submarine [3]

$$\frac{1}{a_0^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_i \partial x_j}\{T_i j H(f)\} - \frac{\partial}{\partial t}\{\left[P_{ij} n_{ij} + \rho u_i (u_n - v_n)\right]\delta(f)\} + \frac{\partial}{\partial t}\{[\rho_0 v_n + \rho(u_n - v_n)]\delta(f)\} \quad (5)$$

Where p', is the far field sound pressure ($p' = p - p_0$), T_{ij} is the Lighthill tensor and a_0 is the sound velocity in the far field. The terms at RHS are defined as quadruple, dipole and monopole source, respectively. Also $\delta(f)$ and $H(f)$ are Dirac delta function and the Heaviside function, respectively.

IV. Numerical Method

A. Geometry and Boundary Condition

Darpa Suboff geometry and main particulars are given below in Fig. 3 and Table 2, respectively.

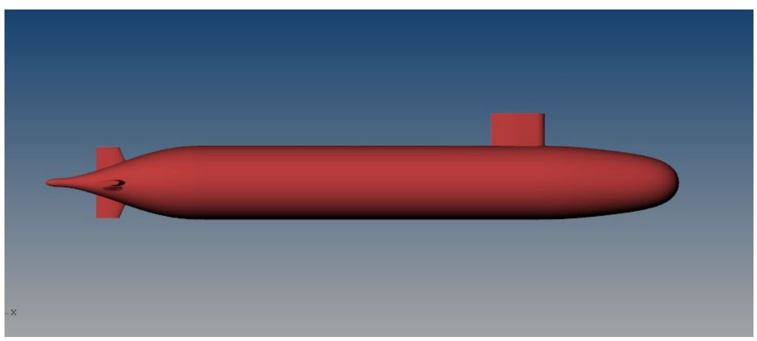

Fig. 3 DARPA Suboff Geometry.

Table 2 Main particulars of DARPA Suboff (Groves et al., 1989).

λ	24
$L_{OA}\,(m)$	4.356
$L_{BP}\,(m)$	4.261
$D_{max}\,(m)$	0.508
$S\,(m^2)$	6.348
$\Delta\,(m^3)$	0.706

Figure 4 shows computational domain and figure 5 shows boundary conditions. The right and left sides of the computational domain have been defined as velocity inlet and pressure outlet, respectively. The submarine has been defines as no slip wall to impose the kinematic boundary condition. The surrounding surfaces have been defined as symmetry plane. towing tank.

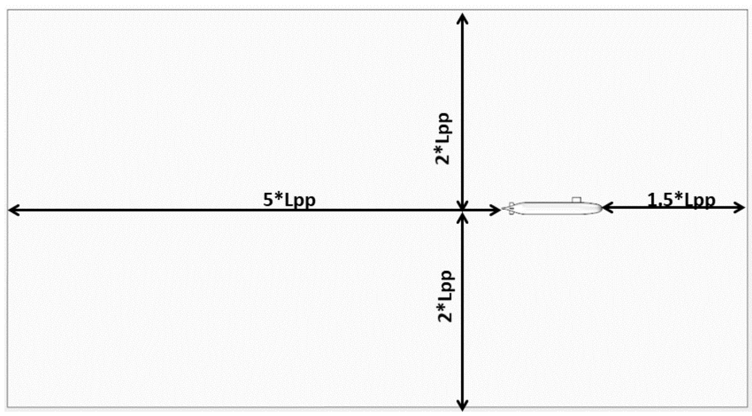

Fig. 4 Computational Domain of DARPA Suboff.

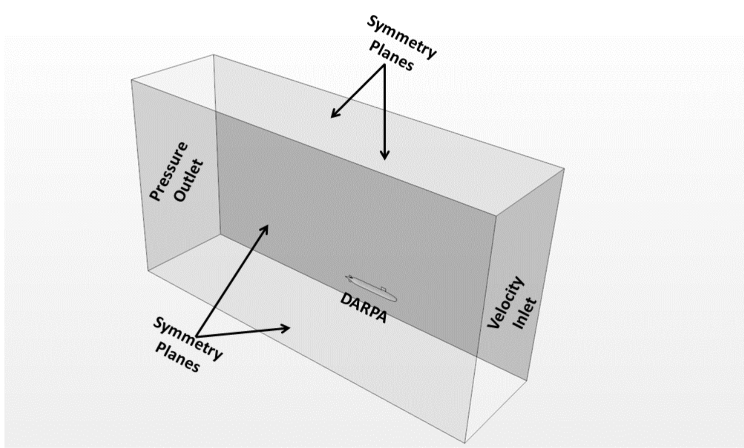

Fig. 5 Boundary Conditions of DARPA Suboff.

B. Grid Generation

For resistance analyses, unstructured hexahedral elementshas been created around the submarine. Trimmer mesh algorithm has been used to create control volume and thus the fully hexahedral mesh structure has been obtained.

Unstructured mesh around the submarine has been given in Figs. 6. hull surface mesh size has been adjusted in order to keep wall y+ values in an acceptable range (30–300). Average wall y + value of the submarine hull is around ∽ 100 for all velocities.

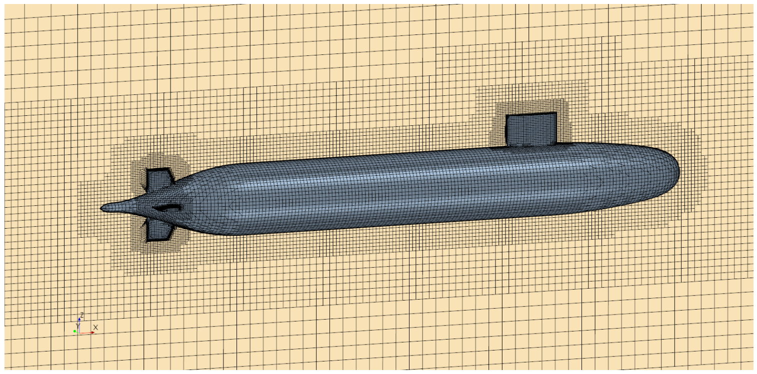

Fig. 6 Unstructured mesh around DARPA Suboff.

V. Hydrodynamic and Hydroacoustics Validation

Experimental and RANS Method results of Darpa Suboff submarine are shown in Fig.7. Experimental data have been taken from [6].As shown in Fig. 7, the results of RANS method agree well with those of experiments.

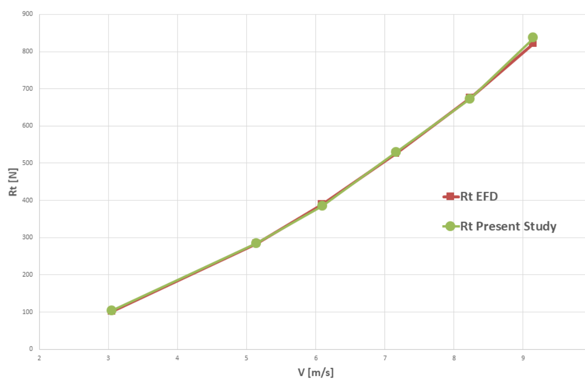

Fig. 7 Comparison of total resistance for submarine

The flow noise of AFF-8 has been investigated using both u-RANS method and FW-H equations. The acoustic sound pressures in time domain have been computed by the receivers. The receivers location around the submarine are given below.

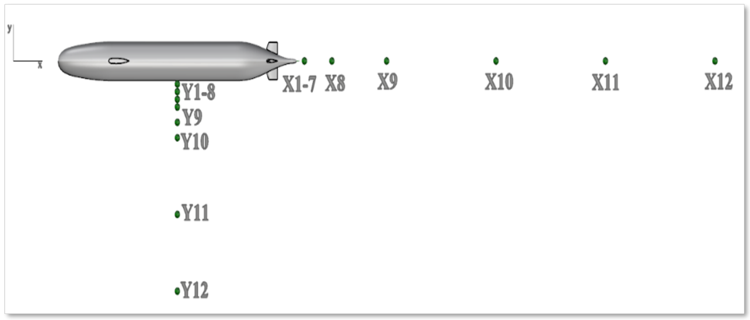

Fig. 8 Receivers around submarine

Both Sound Pressure Level (SPL) and Overall Sound Pressure Level (OASPL) have been compared with Yao et al.[6] In the following figure the red line is FH-H results of present study and the blue line are LES and BEM results of Yao, respectively. According to these results, it was found that the results of the present study were closer to those LES results given in Yao's study.

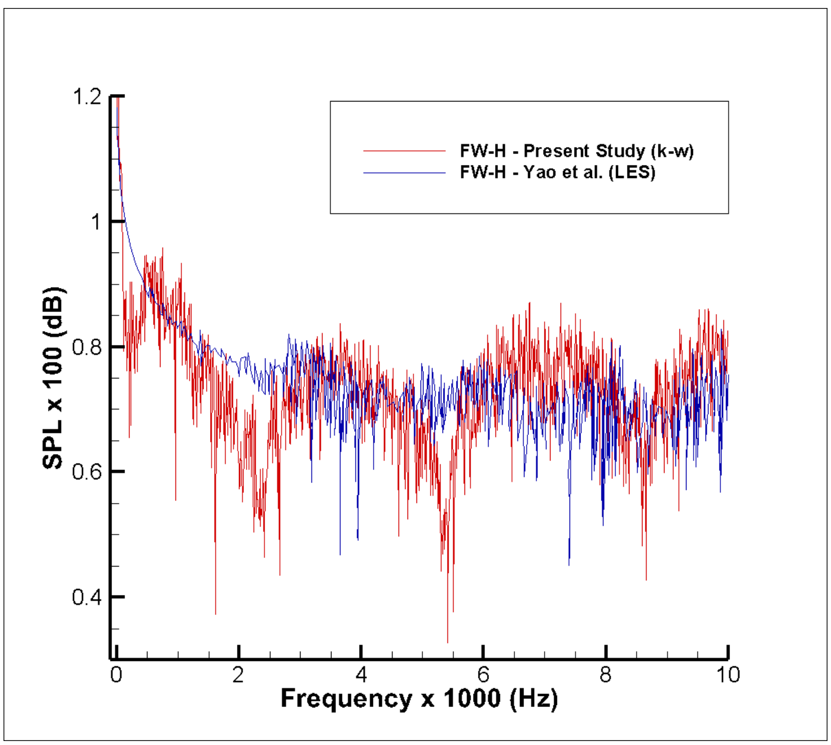

Fig. 9 Comparison of SPL values with Yao et al.(Receiver X1)

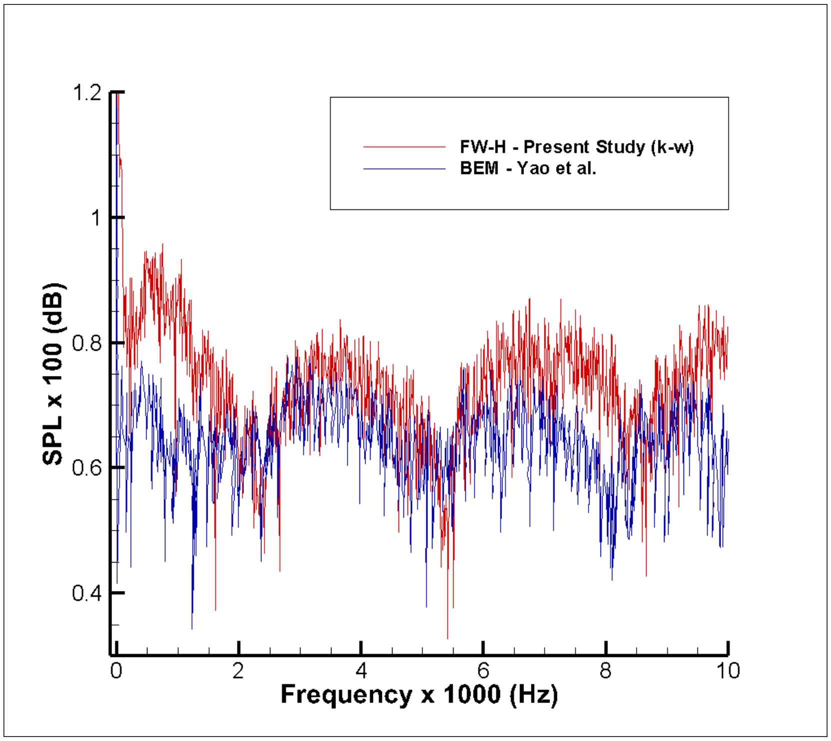

Fig. 10 Comparison of SPL values with Yao et al.(Receiver X1)

Figure 11 shows the results OASPL of flow noise along x-direction amd Figre 12 shows the results OASPL of flow noise along y-direction The red line is present study. The numerical results of RANS method in present study are higher than of BEM methods in y-direction. These differences may be due to more precisely modeling of RANS approaches rather than BEM method. However, the present results are slightly in accordance with LES results of Yao's study.

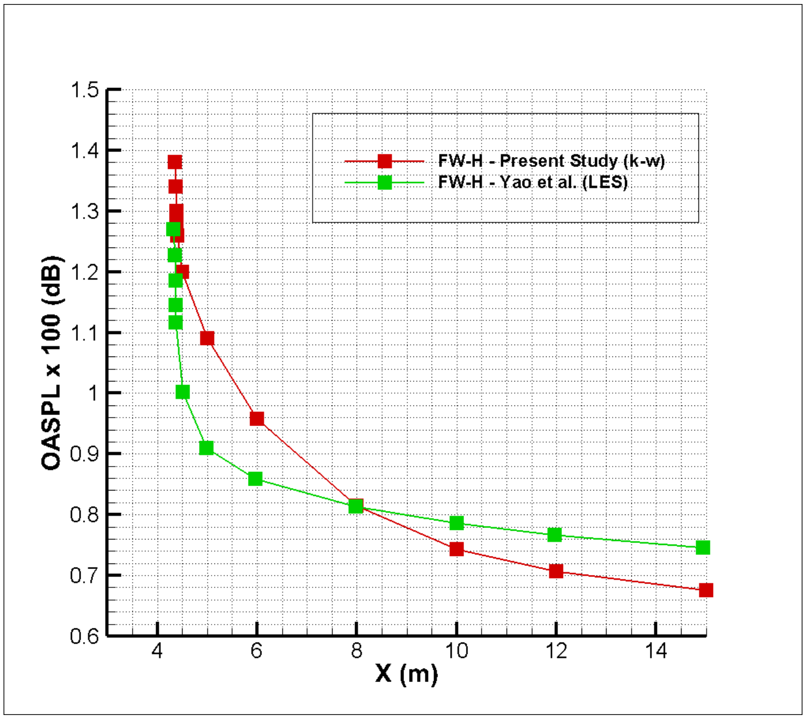

Fig. 11   OASPL of flow noise along x-direction

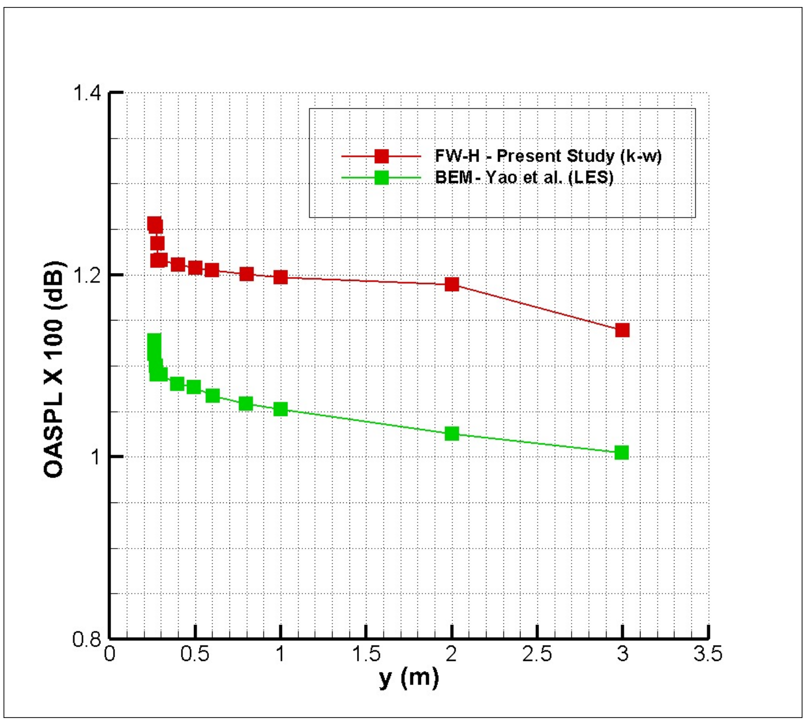

Fig. 12   OASPL of flow noise along y-direction

VI. Optimization

Optimization study has been performed according to the framework given in appendix A.

A. Sobol Algorithm

In Sobol phase, 400 variant for resistance analysis and 40 variant for hydroacoustics analysis have been created. Since Sobol is one of the most succesfull space filling algorithms, high fidelity model solutions obtained from it will be the input of the surrogate model in the next step.

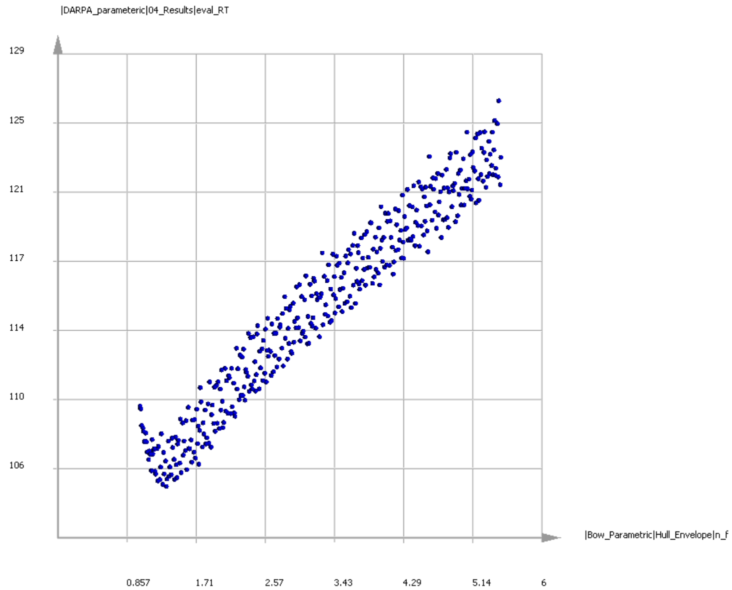

Fig. 13 Sobol Results

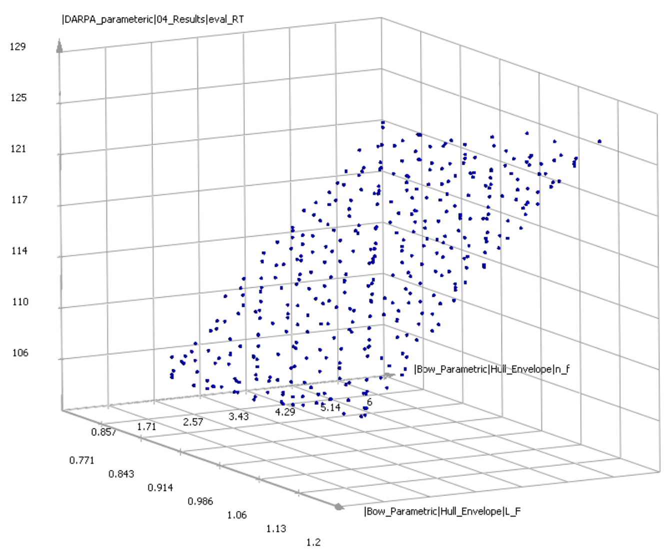

Fig. 14 Sobol Results

B. Response Surface

LinearNDInterpolator function in the Scipy library of Python was used to create the surrogate model and response surface.

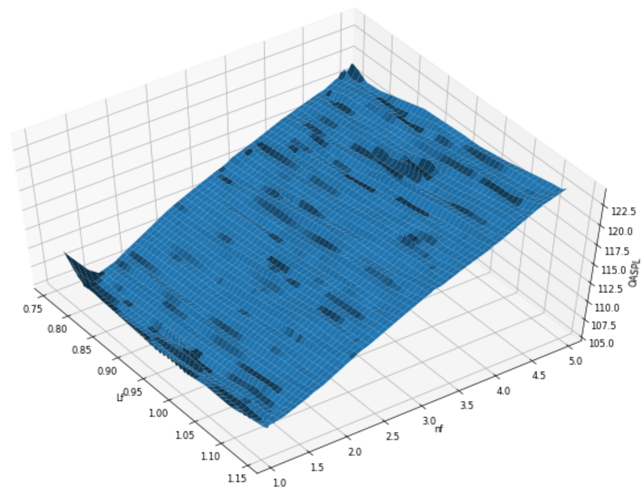

Fig. 15 Responce surface-Resistance

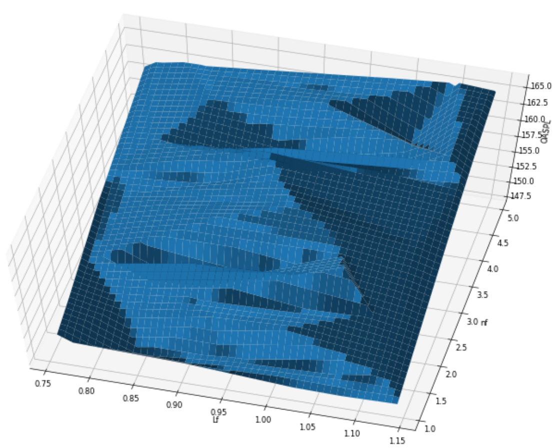

Fig. 16 Responce surface - OASPL

C. NSGA-II Algorithm

After creating response surface for resistance and hydroacoustics, optimization process have been performed using NSGA-II algorithm. 10 generations that have the population size of 50 variants have been created with the genetic algorithm parameters Mutation and Crossover Possibility 0.1 and 0.9 respectively. Figure 17 and Figure 18 shows results of NSGA-II.

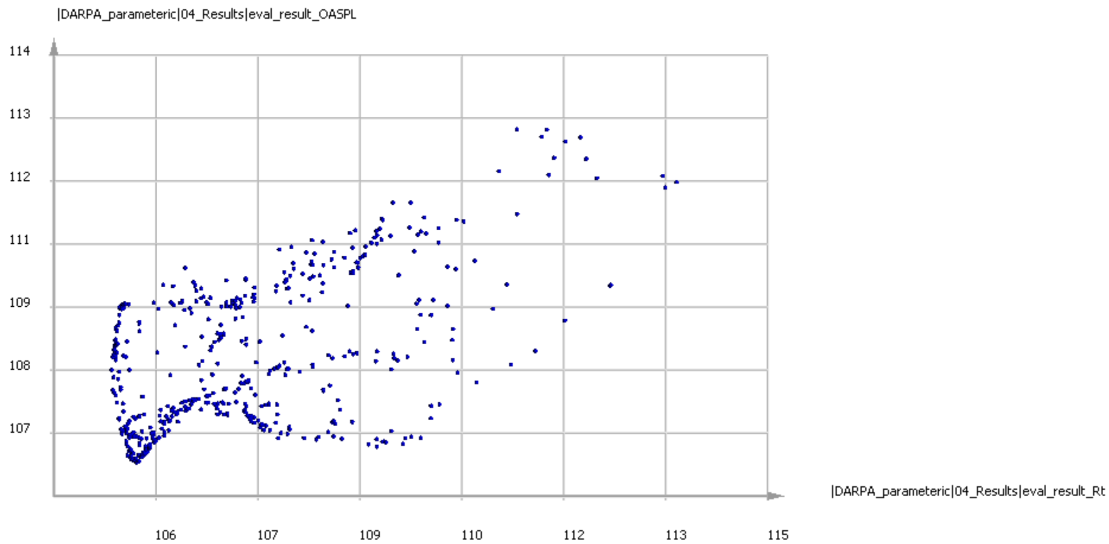

Fig. 17 NSGA-II Results-Pareto

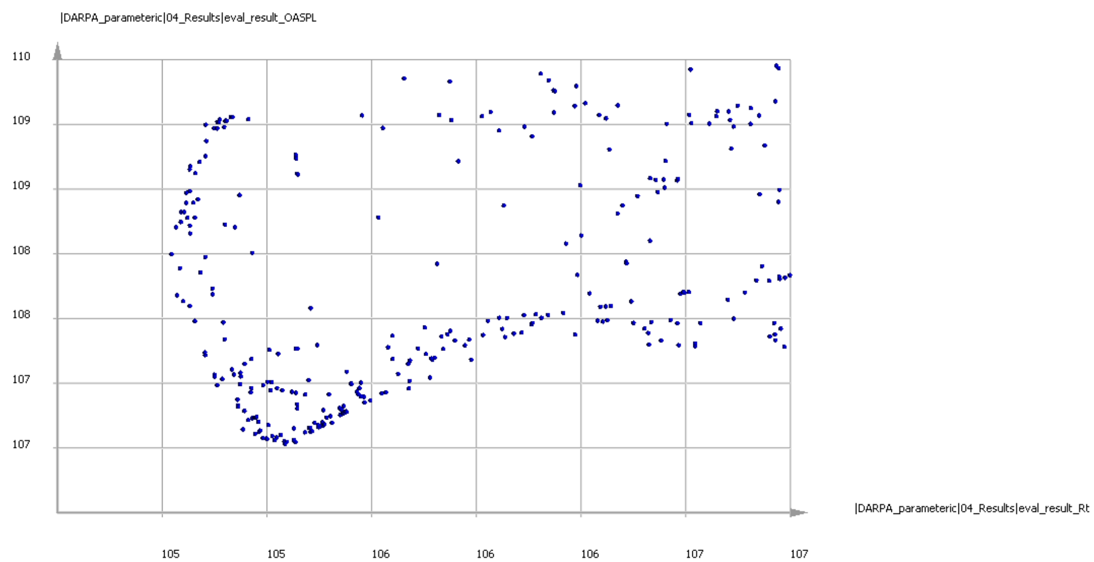

Fig. 18 NSGA-II Results-Pareto

After the optimization process, 520 variants were created. 21 best results models have been found as Pareto Optimal after running NSGA-II algorithm. Figure 19 shows the best results.

	L_F	n_f	eval_result_Rt	eval_result_OASPL
Nsga2_07_des0131	0.81419165	1.3429618	104.92843	107.86811
Nsga2_07_des0288	0.81547341	1.3469902	104.95107	107.82636
Nsga2_07_des0318	0.83979019	1.3310597	105.13162	106.73534
Nsga2_07_des0327	0.82373159	1.285832	105.03522	107.218
Nsga2_07_des0352	0.84968414	1.3398489	105.2738	106.63103
Nsga2_07_des0368	0.84582666	1.3409247	105.24054	106.64075
Nsga2_07_des0375	0.83723888	1.3037079	105.11626	106.93464
Nsga2_07_des0400	0.82619135	1.2828565	105.04437	107.12696
Nsga2_07_des0411	0.8239147	1.3385901	105.00262	107.41532
Nsga2_07_des0424	0.84193866	1.340856	105.20033	106.65848
Nsga2_07_des0440	0.84348287	1.340238	105.21256	106.65587
Nsga2_07_des0441	0.83344854	1.3409018	105.11366	106.99704
Nsga2_07_des0444	0.81808576	1.3429618	104.96831	107.69359
Nsga2_07_des0446	0.81189059	1.329778	104.90765	107.91988
Nsga2_07_des0458	0.84328145	1.3539025	105.27615	106.607
Nsga2_07_des0462	0.82829709	1.3343557	105.03545	107.20242
Nsga2_07_des0472	0.80485313	1.3424125	104.88827	108.28451
Nsga2_07_des0473	0.83698863	1.3021286	105.11452	106.9466
Nsga2_07_des0482	0.82440299	1.3378576	105.00337	107.39058
Nsga2_07_des0510	0.84328145	1.3409018	105.21435	106.6522
Nsga2_07_des0512	0.84269551	1.3349966	105.17408	106.69539

Fig. 19 Best Results

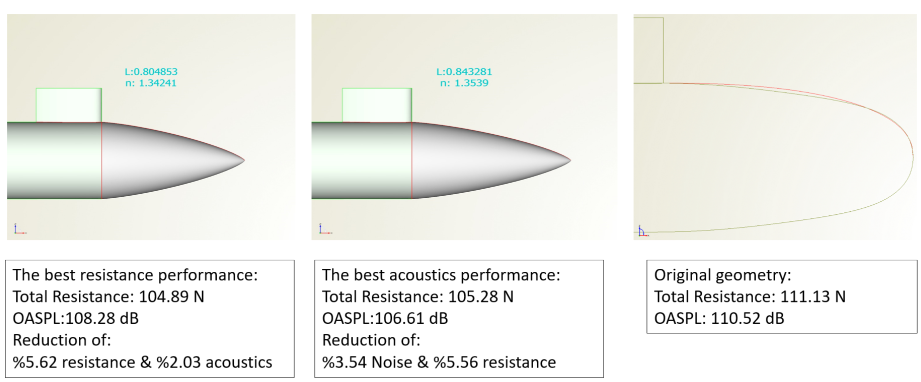

Fig. 20 Optimal results for resistance, oaspl and improvements of the designs.

Bow form on the left, des0472, represents the best resistance performance with 104.888N. Besides, the middle figure belongs to the des0458 that has the best acoustic values with 106.607 dB. Taking into account of the values original geometry, it can be deducted that %5.62 reduction for resistance and % 3.54 reduction for acoustic values have been obtained.

VII. Conclusion and Future Work

In this study, flow around Darpa Suboff submarine was numerically investigated and the geometry was optimized to increase hydrodynamic efficiency and decrease underwater radiated nose..

First of all, validation of the resistance analysis model was carried out using experimental results. The results of RANS method agree well with experimental data.

For hydroacoustics validation, both Sound Pressure Level (SPL) and Overall Sound Pressure Level (OASPL) was compared with Yao's study.It was found that the results of the present study were closer to those LES results given in Yao's study.

After validation study, optimum bow shape of Darpa Suboff submarine geometry was investigated to increase hydrodynamic efficiency and decrease underwater radiated noise.In Sobol phase, 400 variant for resistance analysis and 40 variant for hydroacoustics analysis was created and response surface was created with the results obtained.The response surfaces were used in NSGA-II algorithm. Finally, the optimization process with NSGA-II algorithm was applied and 21 besut results was obtained.

In the future work, it is planned to perform an optimization study for the same geometry including the fluid-structure interaction effects in the problem.

References

[1] Lighthill, M., "On Sound Generated Aerodynamically. I. General Theory." *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences 211 (1107): 564–87.*, 1952.

[2] Curle, N., "The Influence of Solid Boundaries upon Aerodynamic Sound. Proceedings," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 231 (1187): 505–14*, 1955. https://doi.org/10.1098/rspa.1955.0191.

[3] Williams, J. F., and Hawkings, D. L., "Sound generation by turbulence and surfaces in arbitrary motion." *Philosophical Transactions of the Royal Society of London*, Vol. 264, 1969, pp. 321, 342.

[4] Chen, L., and MacGillivray, I., "Characteristics of sound radiation by turbulent flow over a hydrofoil and a bare-hull SUBOFF," *Proceedings of Acoust Conference; 2011.*, 2011.

[5] Yao, S., Guang, P., and Gao, H., "LES-Based numerical simulation of flow noise for UUV with full appendages. Adv Mater Res 2013;631:879–84." *Mater Res 2013;631:879–84.*, 2013. https://doi.org/https://doi.org/10.4028/www.scientific.net/AMR.631-32.879.

[6] Yao, H., Zhang, H., Liu, H., and Jiang, W., "Numerical study of flow-excited noise of a submarine with full appendages considering fluid structure interaction using the boundary element method," *Engineering Analysis with Boundary Elements*, Vol. 77, 2017, pp. 1, 9. https://doi.org/https://doi.org/10.1016/j.enganabound.2016.12.012.

[7] Moonesun, M., Korol, Y., Nikrasov, V., Ursalov, A., and A.Brajhko, "CFD analysis of the bow shapes of submarines," *Journal of Scientific and Engineering Research*, 2016.

[8] Moonesun, M., Korol, Y., Dalayeli, H., amd M. Javadi, D., Jelokhaniyan, M., and Mahdian, A., "Optimization on submarine stern design," *Journal of Engineering for the Maritime Environment*, 2016. https://doi.org/https://doi.org/10.1177/1475090215625673.

[9] Wilcox, D. C., *Turbulence Modeling for CFD*, 3rd ed., chapter and pages.

Appendix - A

OPTIMIZATION WORKFLOW FOR OPTIMIZATION OF DARPA SUBOFF