Hydrophone Acoustic Receiver Modeling: Turbulent Flow Modeling and Acoustic Analysis

A. Bharath, D. Groulx* and S. Campbell
[1] Department of Mechanical Engineering, Dalhousie University, Halifax, NS, Canada
*dominic.groulx@dal.ca

Abstract: The field of underwater acoustics research is constantly growing with the ongoing improvement of acoustic measuring techniques. An acoustic hydrophone receiver is a passive listening device which is widely used in biological research and sonar technology. The hydrophone however suffers from turbulence generated noise created by its presence in ever faster flow. This work aims to analyze the pressure variations on a hydrophone receiver in flows with Reynolds numbers < 30,000 and quantify the acoustic power generated in the turbulent wake of the hydrophone using COMSOL Reynolds Averaged Navier-Stokes (RANS) fluid modelling physics.

Keywords: Hydrophone, RANS, Turbulence, Acoustic Power.

1. Introduction

The effect of acoustic noise on marine wildlife has become an area of increasing interest with the increasing usage of ocean energy for electrical power generation. International regulations have been introduced in Europe and North America to protect the ocean acoustic environment [1]. Ongoing research into the impact of acoustic marine pollution from both natural and unnatural phenomenon demands accurate data concerning the generation and propagation of acoustic noise throughout the oceans [2].

OceanSonics, an ocean technology company, is actively developing hydrophone technologies to collect increasingly accurate acoustic data. They hydrophone device itself suffers from noise contamination which obscures the desired acoustic signals. Self-noise pressure variations in standing water are well understood and hydrophone technology has been shown to be capable of accurately measuring this noise background [3]. A lesser understood area of noise production in hydrophone signals is that caused by turbulent motions. Statistical methods for describing turbulence given by [4], is a general method for a turbulence analysis. The work in [5] and [6] describe methods for estimating the noise based on statistical turbulence quantities. The method given in [5] is used in this work to estimate the acoustic power in the wake of the OceanSonics hydrophone in various free stream velocities.

Apart from the acoustic power in the flow downstream from the hydrophone, a major contribution to the noise in a hydrophone signal is the pressure variations on the hydrophone receiver surface. The work in [7] reports on the capabilities of the standard $k-\varepsilon$ RANS model when simulating. This model formulation is available in COMSOL and is used for the simulations used in this work.

This work aims to visualize and quantify the flows and acoustic noise generated by the presence of a hydrophone. The pressure field appearing on the surface of the hydrophone is analyzed and compared to Large Eddy Simulation (LES) results obtained with ANSYS Fluent. The acoustic power and modelled turbulence quantities k and ε are presented and linked to design features on the hydrophone.

2. Governing Equations

The main goal of this work is to analyze the acoustic power that is generated in the wake of the hydrophone. A relationship between the mean-square velocity fluctuations and the acoustic power are defined as [5]:

$$\boldsymbol{P} = -\frac{3}{2}\boldsymbol{\alpha}\frac{\overline{d\boldsymbol{u}^2}}{d\boldsymbol{t}}\left(\frac{\boldsymbol{u}^2}{\boldsymbol{c}^2}\right)^{\frac{5}{2}} \quad (1)$$

where α is a numerical constant and c is the speed of sound in the medium. Rewritten in terms of turbulent kinetic energy k and the turbulent dissipation rate ε as,

$$P = \alpha_\varepsilon \rho \varepsilon \frac{(2k)^{\frac{5}{2}}}{c^5} \quad (2)$$

where the rescaled constant α_ε is set to 0.1 following [8]. Equations (1) and (2) give an approximation of the local contribution to the total acoustic power per unit volume in a turbulent field. Given the Reynolds numbers for the flows around the hydrophone and the small Mach number, this should serve as a good quantity to estimate the acoustic power.

The standard $k-\varepsilon$ model is used to solve for the turbulent kinetic energy and dissipation rate parameters needed for the acoustic power calculation follow the two equation closure scheme described in [9] and formulated in COMSOL as,

$$\rho(\boldsymbol{u}\cdot\nabla)k = \nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_T}\right)\nabla k\right]+\cdots + P_k - \rho\varepsilon \quad (3)$$

$$\rho(\boldsymbol{u}\cdot\nabla)\varepsilon = \nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\cdots + C_{e1}\frac{\varepsilon}{k}P_k - C_{e2}\rho\frac{\varepsilon^2}{k} \quad (4)$$

where $\sigma_k, \sigma_\varepsilon, P_k, C_{e1}, C_{e2}$ are all model constants given in Table 1. Equations (3) and (4) coupled with the usual Reynolds averaged Navier-Stokes and continuity equations provide the necessary numerical accuracy to accomplish the goals of this work [**Erreur ! Source du renvoi introuvable.**]. A more details description of the COMSOL model is given in the following section.

3. Use of COMSOL Multiphysics

COMSOL Multiphysics 4.4 was used in each aspect of the hydrophone CAD, numerical simulation and post-processing. The model domain used in simulations is shown in Fig. 1. The inlet upstream of the hydrophone is a velocity inlet with turbulence intensity I_T and the turbulent lengthscale L_T held at 0.05 and 0.01 m respectively. The pressure outlet was set to suppress backflow and all other domain boundaries were set as no-slip walls with standard $k-\varepsilon$ wall functions applied.

The domain mesh was created using the COMSOL meshing tool calibrated for fluid dynamics concentrating element density near the hydrophone. The surface mesh on the hydrophone is shown in Fig. 2.

Table 1. Model constant values used in COMSOL simulations.

σ_k	σ_ε	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$
1	1.3	1.44	1.92

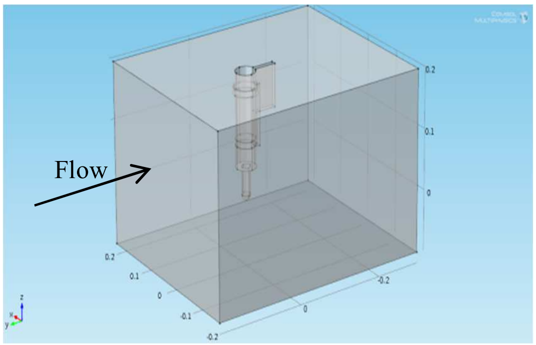

Figure 1. The domain and CAD model of the OceanSonics hydrophone developed entirely in COMSOL.

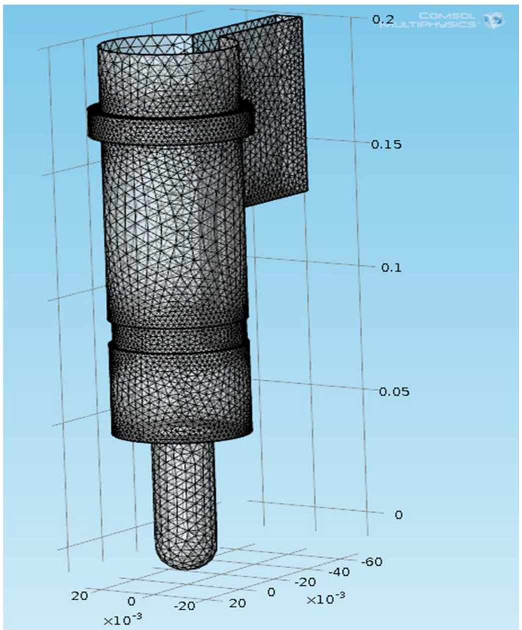

Figure 2. The surface mesh on the hydrophone created with the COMSOL meshing tool.

A 9 layer boundary mesh was created on each hydrophone surface with a stretching factor of 1.15 to ensure proper wall function application. The domain surrounding the hydrophone was filled with a free tetrahedral up to a maximum element size of 1.2 cm. The number and type of elements included in the final mesh are shown in Table 2.

Table 2. Shape and number of elements incorporated into the domain mesh created around the hydrophone.

Element Type	Number of Elements
Tetrahedral	684732
Pyramid	8846
Prism	65930
Triangular	23028
Quadrilateral	422
Edge	1333
Vertex	40
Total	759508

The post-processing tools available in COMSOL were for direct analysis of the flow field results. The LiveLink connection to Matlab allowed for the simple implementation of functions which were not immediately available. The flow field and acoustic power results generated from the COMSOL simulations are given in the following section.

4. Results

4.1 Flow Field

COMSOL fluid flow simulations around the hydrophone were conducted at free stream velocities of 1 to 4 m/s to mimic typical flows in the Bay of Fundy. The velocity field profiles in the wake of the receiver are shown in Fig. 3. The velocity gradients near the surface of the hydrophone receiver indicate turbulent flow separation on this upstream facing section of the receiver surface which agrees with LES results. The turbulent separation corresponds to a pressure field distribution on the hydrophone receiver face. The spatially averaged pressure field on the receiver face is the measure quantity making it of great importance to this work. The pressure field distribution on the hydrophone receiver face is shown in Fig. 4.**444**

The pressure field on the hydrophone receiver from COMSOL shows a region of high pressure on the surface facing the flow giving way to regions of low pressure near the cylinder apexes perpendicular to the direction of flow. The positive to negative pressure transition highlights the point where laminar flow transitions to turbulent seen in Fig. 3. The downstream face of the receiver experiences irregular fluctuations in pressure as a result of the wake. This region has a significant impact on the average pressure seen on the receiver as the field magnitudes are determined by the intensity of turbulent motions in the wake. Figure 5 shows the change in average pressure on the receiver surface with increasing free stream velocity.

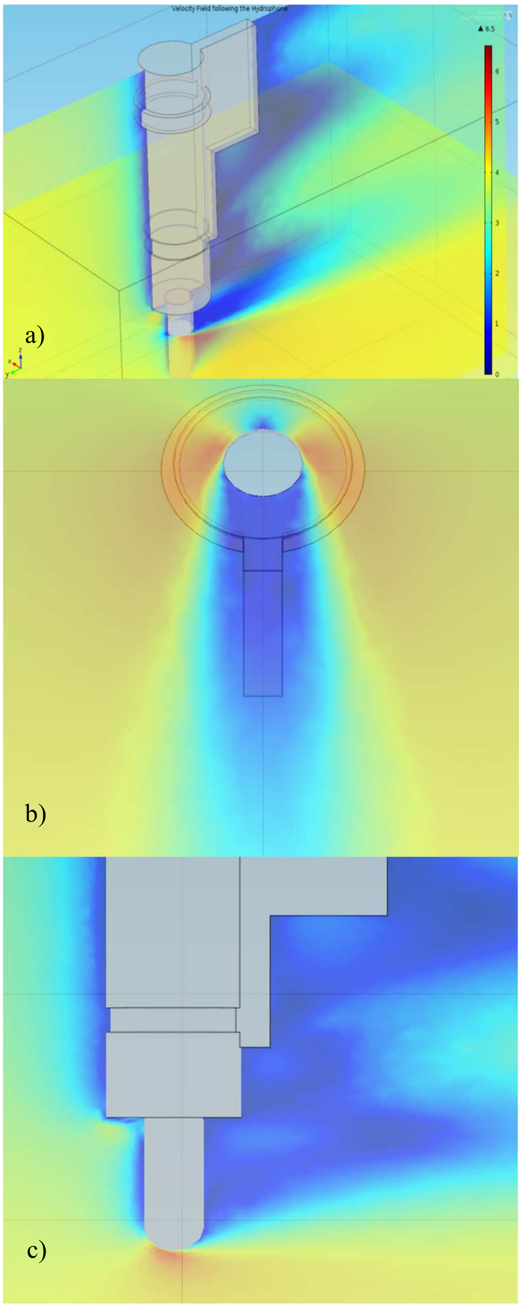

Figure 3. The velocity field surrounding the hydrophone at a 4 m/s free stream velocity. a) an angled visualization of the flow, b) a bottom up view of the wake and c) a side on view.

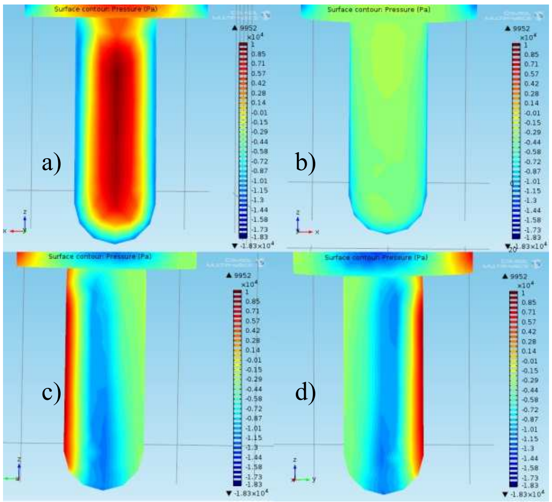

Figure 4. The pressure field on the hydrophone receiver showing views a) face perpendicular to incoming flow (front) b) face perpendicular to outgoing flow (back) c) left side parallel to flow d) right side parallel to flow.

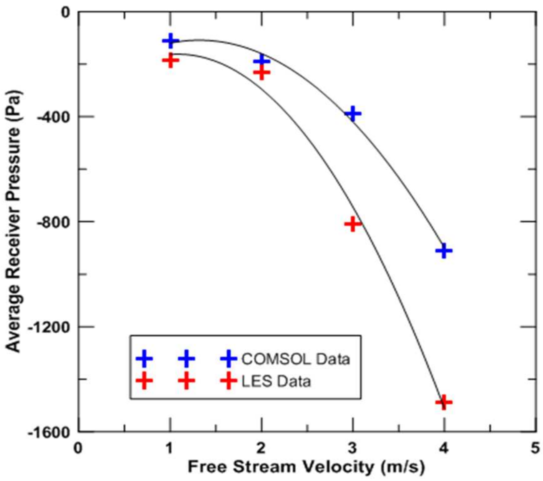

Figure 5. Average pressure on the receiver surface with increasing free stream velocity.

When compared to LES results, COMSOL simulations tend to over predict the average pressures seen on the receiver surface. The decreasing trend with increasing free stream velocity however is well captured in the simulations. The LES model formulation aims to resolve true flow field fluctuations which are not resolved by the $k-\varepsilon$ parameterization which would account for the small discrepancy in surface pressure magnitudes. The flow field surrounding the hydrophone including the connection between the hydrophone body and receiver tip closely resembles that which is seen in LES results. With the COMSOL representation of the flow field, it is possible to predict magnitude of acoustic power generated by the hydrophone in the flows.

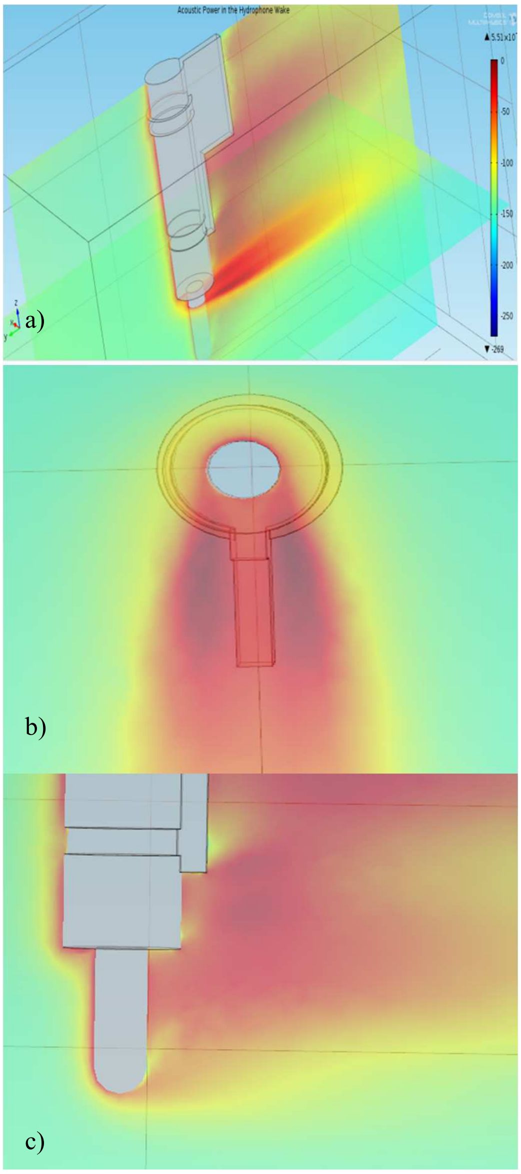

Figure 6. The acoustic field generated in the turbulent wake following the hydrophone in a 4 m/s flow. The log scale is in reference to the maximum acoustic power in the domain. a) an angled visualization of the flow, b) a bottom up view of the wake and c) a side on view.

4.2 Acoustic Power and Turbulent Quantities

The acoustic noise generated by the turbulent motions in the wake of the hydrophone causes low frequency distortions which saturates the desired signal. Then following equation (2), the acoustic power generated in the wake can be estimated with the $k - \varepsilon$ turbulence model (Eqs. (3)-(4)). A visualization of the acoustic field is shown in Fig. 6.

The acoustic power achieves a maximum value in all simulations in the wake following the junction between the receiver tip and the larger radius body. Figure 4 shows a tendency for a more neutral pressure field along the circumference of the receiver which indicates a level of turbulence intensity in this area. More energy in the flow is held in turbulent motions which decreases the pressure exerted on the receiver surface and generates the bulk of the acoustic noise.

The distribution of acoustic power in the model domain for each modelled free stream velocity is shown in Fig. 7. The acoustic power away from the hydrophone wake is minimal as inlet flows contained limited simulated turbulence.

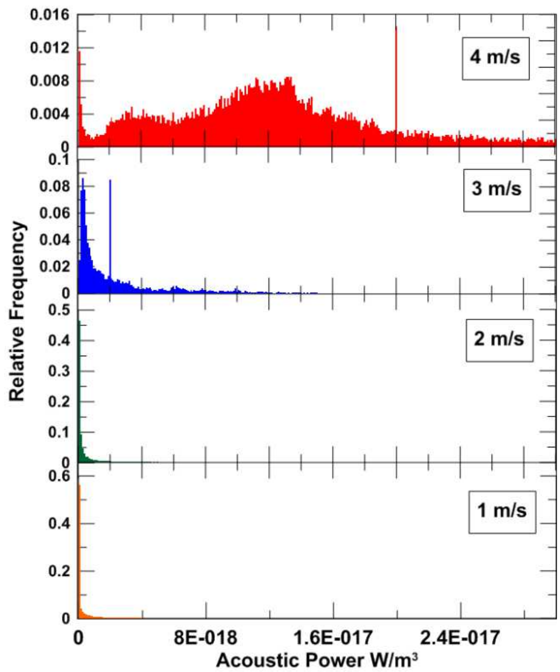

Figure 7. The acoustic power distributions in the model domain.

Figure 7 however shows the increasing amount of acoustic power in the hydrophone wake. Free stream velocities of 1 and 2 m/s show a quick drop off relative to the faster flows. The 3 and 4 m/s flows show similar acoustic power distributions which implies similar levels of noise in the wake. Table 3 gives statistical values for the acoustic power in the hydrophone wake.

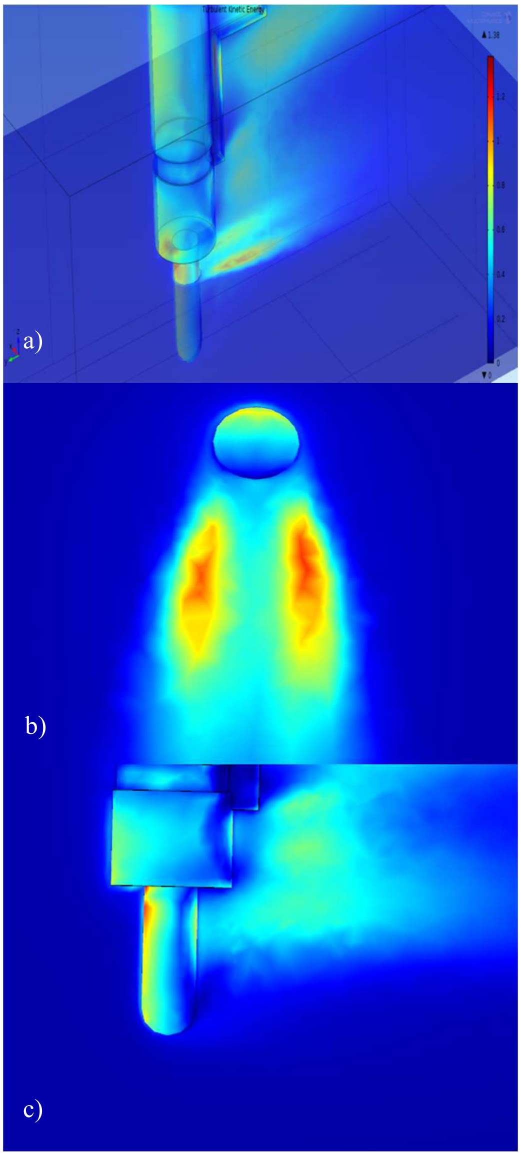

Figure 8. Turbulent kinetic energy (J/kg) following the hydrophone in a 4 m/s free stream velocity flow. a) an angled visualization of the flow, b) a bottom up view of the wake and c) a side on view.

Table 3. Acoustic power level statistics for the various free stream velocities. Quantities are given in W/m^3.

Flow Speed	Mean	Standard Deviation	Maximum
1 m/s	2.8×10^{-17}	1.04×10^{-16}	3.68×10^{-15}
2 m/s	2.96×10^{-15}	1.58×10^{-14}	2.03×10^{-12}
3 m/s	1.07×10^{-13}	5.08×10^{-13}	3.05×10^{-11}
4 m/s	1.5×10^{-13}	1.15×10^{-12}	1.66×10^{-11}

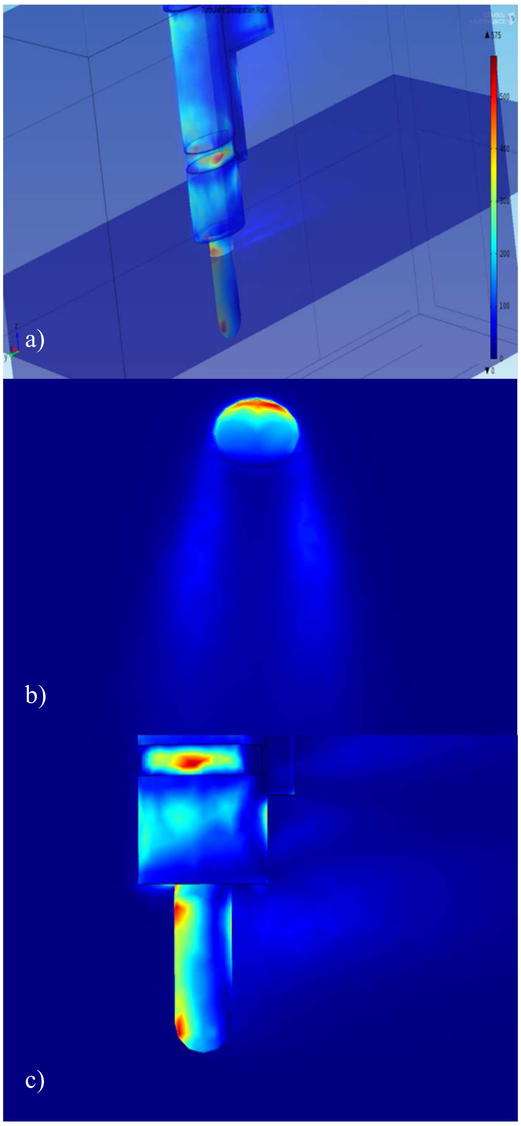

Figure 9. Turbulent dissipation rate (W/kg) following the hydrophone in 4 m/s free stream velocity flows. a) an angled visualization of the flow, b) a bottom up view of the wake and c) a side on view.

777777 Table 3 indicates a four order of magnitude increase in mean acoustic power between 1 and 3 m/s flows. This points to a dramatic increase in turbulence through these velocities. The acoustic power values are closely comparable between 3 and 4 m/s however. The turbulent behavior driving acoustic noise is generated largely by the sharp topological changes along the profile of the hydrophone. Figure 8 shows the turbulent kinetic energy (TKE) developed in the flow by the hydrophone.

Figure 8 indicates that TKE on the surface of the hydrophone receiver is strongest nearer to the larger diameter hydrophone body. This would indicate that design modifications to this area would reduce TKE development and therefore reduce the overall acoustic power in the hydrophone wake. The turbulent dissipation rate also contributes to the acoustic power in the hydrophone wake and is shown in Fig. 9.

The turbulent dissipation rate appears strongest near the hydrophone itself. This indicates that the acoustic power in the wake is predominately generated by the turbulent kinetic energy in the flow. The impact on dissipation becomes increasingly important however when analyzing the acoustic power near the surface of the hydrophone receiver.

5. Conclusions

COMSOL Multiphysics provides the tools to analyze turbulence and acoustic phenomenon generated by the presents of obstructions in a flow field. The OceanSonics Hydrophone design has been modeled giving velocity, pressure and turbulence generated acoustic field predictions. The flow transition between laminar and turbulent regimes seen on the hydrophone receiver appear to match those from LES simulations. Average pressures on the hydrophone receiver with increasing free stream velocity tend to be over predicted in COMSOL while the decreasing trend is well captured. The acoustic power surrounding the hydrophone was found to be similar in 3 and 4 m/s flows, visualized in Fig. 7 and quantified in Table 3.

The next steps in COMSOL turbulence simulations will be to implement various hydrophone design changes in order to eliminate strong point of turbulent generation in order to reduce the acoustic power in the wake. The optimization tools available in COMSOL will be used to systematically determine the effect of design changes to the overall level of acoustic power in the wake.

6. References

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