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Prediction and Experimental Validation of Full Scale Non Cavitating Marine Propeller Noise

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Abstract:

Marine propeller is one of the dominant noise source of marine vehicle. Underwater propeller noise can be classified into cavitating and non-cavitating noise. However, submarines and torpedoes are usually operated deep enough under the sea to avoid cavitation. Compared with the extensive amount of literatures concerning cavitation noise of propellers, works concerning the non-cavitation noise of propellers are hard to find.The purpose of the propeller is to produce the thrust and propel the ship in forward and reverse direction. But it is identified as major noise source.Noise reduction and control is an important challenge for thewarship designers to protect the vehicle from enemy's threat. The ultimate goal of a warship designer is to make the ship's noise signature matches with the background noise of the sea which comprises contributions from the weather, marine life and also other shipping from a wide geographical area. This paper presents a numerical investigation of unsteady non-cavitating turbulent flow around a full scale marine propeller using the Eddy Viscosity model of Large Eddy Simulation (LES) available inFluent software. Propeller behaviour is investigated for its hydrodynamic parameters and then Computational Acoustic Analysis (CAA) is carried out using Ffowcs Williams–Hawkings formulation (FW-H). Here solver is chosen as pressure based, unsteady formulation of second order implicit. Noise is predicted using time-domain acoustic analogy and finite volume method. Sound pressure levels are predicted at different receiver positions. These results are compared with experiments conducted in Cavitation Tunnel using the ''Acoustic Measurement System (AMS)"at NSTL, Visakhapatnam. Predicted results are found to be in close agreement with the measured values.

Keywords: Propeller, Non-cavitating Noise, Computational Acoustic Analysis (CAA), Large eddy simulation (LES), FfowcsWillams-Hawkings formulation (FW-H)

I. INTRODUCTION

1.1 General Description

Propeller noise is critical in underwater detection, and it is often related to the survivability of the vessels for military purposes. The propeller generally operates in a non-uniform wake field behind the marine vehicle. As the propeller rotates, it is subjected to unsteady force, which leads to discrete tonal noise and cavitation. Underwater propeller noise can be classified into cavitating and non-cavitating noise based on the flow regimes. Cavitation of the propeller is the most prevalent source of underwater noise and it is often the dominant noise source of a marine vehicle. Submarines and torpedoes are usually operated under the deep sea enough to avoid cavitation.Numerical investigation of unsteady non-cavitating turbulent flow around a full scale marine propeller is carried out with the eddy viscosity model of Large Eddy Simulation (LES) approach.Propeller behaviour is investigated for its hydrodynamic parameters and then computational acoustic analysis is carried out using Ffowcs Williams–Hawkings formulation. These results are compared with experiments conducted in CavitationTunnel available at NSTL.

1.2 Literature review

Salvatore et al. [1] studied propeller-induced noise emission through a general hydro acoustics formulation based on the Ffowcs Williams-Hawkings (FW-H) equation that allows describing the acoustic pressure field generated by lifting bodies in arbitrary motion through a fluid. Bardyshev [2] measured and analyzed the underwater surf-generated noise near stony, rocky, and sandy coasts of the Black Sea and the Pacific Ocean and presented for a frequency band of 0.03–16 kHz and distances of 0.01–30 km from the coastline. Chang [3] applied a finite volume CFD method in conjunction with the standard k-ε turbulence model to calculate the flow pattern and performance parameters of a DTNSRDC P4119 marine propeller in a uniform flow. The essential step taken by Lighthill [4] was to incorporate the non-linear features of aerodynamic sound generation into a linear acoustic model. There are various ways to evaluate Ffowcs Williams and Hawkings [5] equation and the three types of noise source terms (monopole, dipole, and quadrupole) were proposed. Kuznetsov [6] analyzed and reviewed the consequences of the introduction of new international standards and regulations that impose limitations on the community noise of passenger airplanes and restrict the operation of noisy airplanes. Farrasat and Myers [7] proposed a time-domain formulation that can predict noise from an arbitrarily shaped object in motion without the numerical differentiation of the observer time. Through these studies, the dominant noise source of marine propellers is analyzed, which will provide basis for proper noise control strategies under non-cavitating conditions. Jin-minget al. [8] analyzed the blade frequency noise of non-cavitation propeller in a uniform flow in time domain. The unsteady loading (dipole source) on the blade surface is calculated by a potential-based surface panel method. Then the time-dependent pressure data is used as the input for FW-H formulation to predict the acoustics pressure.Belyaev [9] study concerns the influence of the boundary layer at an aircraft's fuselage, simulated by an infinite hard cylinder, on propeller noise in the acoustic far field. Also studied is the effect of the boundary layer on noise as a function of the thickness and profile of the mean velocity of the boundary layer. Yang et al. [10] presented a new method to measure the propeller noise level in the ship engineering by coupling with LES and boundary element numerical acoustics methods in the frequency domain to predict the underwater non cavitation noise of ship.

Muscariet al. [11] presents the capabilities of numerical simulations with different turbulencemodels (RANSE and DES) to predict the complex flow pattern of propeller have been assessed, the DES method allows to capture the tip vorticesevolution as long as the mesh is reasonably refined with agood qualitative and quantitative agreement with experiments. Pan and Zaang [12] numerical study is on the acoustic radiation of a propeller interacting with non-uniform inflow has been conducted. Real geometry of a marine propeller DTMB 4118 is used in the calculation, and sliding mesh technique is adopted to deal with the rotational motion of the propeller. The performance of the DES (Detached Eddy Simulation) approach at capturing the unsteady forces and moments on the propeller is compared with experiment. Far-field sound radiation is predicted by the formation developed by Farassat, an integral solution of FW-H (Ffowcs Williams-Hawkings) equation in time domain. Jin-Ming et al. [13] presents the blade frequency noise of a cavitating propeller in a uniform flow is analyzed in the time domain. The unsteady loading (of a dipole source) and the sheet cavity volume (of a monopole source) on the propeller surface are calculated by apotential-based surface panel method. Then the time-dependent pressure and the cavity volume data are used as the input for theFowcs Williams-Hawkings formulation to predict the acoustics pressure. Many authors used Reynolds-averaged Navier- Stokes (RANS) for turbulence modeling. However RANS have limitation of capturing details of such transient events like unsteady force and pressure fluctuation of the blade with an acceptable accuracy. In that regard, Large Eddy Simulation (LES) has been considered having merits to resolve the least large scale turbulent structures, which isfurther justifiable for the unsteady flow around propellers operated at the stern of ships.

In the present paper, six bladed propeller is used for the study.The diameter of propeller is 0.389m and hub to propeller diameter ratio is 0.254. Prediction of non-cavitation noise of propeller is carried out by both numerical and experimental methods at rotating speed of 780 rpm, 840 rpm, 900 rpm and 960 rpm at different vehicle forwardspeeds of 7.08 m/s, 7.62 m/s, 8.17 m/s and 8.7 m/s respectively. The noise produced by a propeller is very much importance to warship designers and military strategists for many years. So in this paper an attempt is made to predict the non-cavitation noise of propeller using of FW-H equation coupled with LES computer code based on cell-centered finite volume method(FVM)on unstructured meshes for viscous flow field around propeller. These results are compared with experiments conducted in CavitatonTunnel of size 1m×1m×6 m.

II. NUMERICAL INVISTIGATION

2.1 Flow Solver

The Navier-Stokes Equations do not only describe turbulent flows but also their sound radiation. A direct numerical simulation (DNS) of the sound radiation is not possible with available computer resources for the Reynolds numbers of technical interest. Therefore, the problem is solved via a zonal approach. Only the flow region with hydrodynamic sources is simulated by solving the Navier-Stokes equations with sufficient precision. The far-field radiation is then computed by solving integrals over a control surface based on acoustic analogies. In certain cases it is useful to define intermediate zones in which the sound propagation is solved with methods provided by computational acoustics.

To reduce the computational effort in the source region, the precise DNS is substituted by less expensive methods such as Large Eddy Simulation (LES) or Detached Eddy simulation (DES). Both methods rely on modeling the smaller scales while the larger scales are resolved in space and time. The difference between LES and DES lies in the treatment of the turbulent boundary layers. The resolution requirement for LES method in the near wall region leads to unfeasibly fine grids for higher Reynolds number flows. DES method is a hybrid RANS-LES method that applies RANS to the near-wall region and LES to separated flow regions. DES method is aimed at bridging the gap that exists between conventional Remolds averaged nervier stokes (RANS) and LES methods in terms of computational expense and predictive accuracy.

2.2 Acoustic Prediction

Lighthill proposed the acoustic analogy in the 1950s.Ffowcs Williams–Hawkings(FW-H) generalized the Lighthill acoustic analogy and included the effects of the general surfaces in the arbitrary motion in 1969. The FW-H equation is an appropriate tool for predicting the noise generated by the complex motion of the solid bodies. Today, almost all deterministic rotor noise predictions are based on the FW-H equation. In recent years, various solutions were derived for the FW-H equation either in the frequency domain or in the time domain. In the early 1970s, most noise predictionmethods were in the frequency domain because thetime-domain methods generally require powerfulcomputers. The analytical solutions were obtained forsome significant problems using the frequency domainanalysiswith some approximation. In the frequencydomain analysis, the blade loading is oftendistributed on the ideal surface without thickness insteadofthe true blade boundary surface, and someapproximation is also made for the distance betweenthe noise source and the observer.Farassat developed several formulations for thesolution of the FW-H equation in the time domain. In particular, the formulation provides a solution forthe monopole and dipole tonal sources for a givengeometry, displacement and aerodynamic loading ofthe moving bodies. The implementation of these formulations quite straightforward because the contributionsfrom each propeller surfaces with different retarded timeis added to form an acoustic wave. The solutionsneed an estimation for the retarded times and an accuraterepresentation for the blade loading.

The theory of hydrodynamic sound was developed by Lighthill [3]. He rewrote the Navier-Stokes equations into an exact, inhomogeneous wave equation whose source terms are important only within the turbulent region. Lighthill acoustic analogy equation is given below

$$\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\nabla^2\right)\left[c^2\left(\rho-\rho_0\right)\right]=\frac{\partial^2 T_{ij}}{\partial_{xi}\partial_{x\,j}} \qquad (1)$$

The acoustic analogy generalized by Ffowcs Williams and Hawkings is often applied in the prediction of the noise emission generated by the rotors of helicopters, axial fans and propellers.

Ffowcs Williams &Hawkings equation is written in the following form

$$\frac{1\partial^2 p}{c^2\partial t^2}-\Delta^2 p=\frac{\partial q}{\partial t}-\frac{\partial F_i}{\partial x_i}+\frac{\partial^2 T_{IJ}}{\partial x_i \partial x_j} \qquad (2)$$

Which shows three types of sources on the right hand side

1) Monopolar, which results from introducing a mass (per unit volume) into the considered area.
2) Dipolar, that takes into account the hydrodynamic forces (F_i).
3) Quadrupolar, due to the turbulence and represented by the Lighthill's tensor.

The basic noise source in propeller is dipolar noise source as generated due to hydrodynamic pressure fluctuation.

2.3 Methodology

In the present paper, propeller consisting of six blades was considered for study. The diameter of propeller is 0.389m and hub to propeller diameter ratio is 0.254. Modeling of the propeller is done using CATIA V5R16. In order to model the blade, it is necessary to have sections of the propeller at various radii. These sections are drawn and rotated through their respective pitch angles. Then all rotated sections are projected onto right circular cylinders of respective radii as shown in Fig. 1. Now by using multi section surface option, the blade is modeled. The surface model is created by enclosing the entire surfaces as shown in Fig. 2.

The objective of the present CFD and acoustic analyses are to find the noise sources and overall SPL of a propeller at receiver point. Fig. 3 shows the computational domain used for preset study. Three dimensional structural tetrahedral grids are generated to descretize the domain. In order to obtain better results tetrahedral element has been used by taking advantage of mesh consistency. The domain is discretized by minimum 10 linear elements per source wavelength to increase the accuracy of the acoustic propagation. In order to give an estimation of the numerical uncertainty, different grid levels are used. Commercially available grid generation code GAMBIT is used to mesh the entire domain of propeller. Convergence is checked with various element sizes and it is observed that close results are observed with element size 8, 10 and 12 so finally element size 12 is used for mesh generation. After convergence there are 436445 and 680134 tetrahedral elements are in the inner volume (propeller volume) and outer volume (far field volume) respectively. Fig. 4 shows the meshed model of propeller in inner volume.

The numerical simulations have been carried out with a finite volume code method using FLUENT. The turbulent nature of the flow is incorporated through the LES. LES is chosen as viscous model because, it needs time dependent solution for hydrodynamic solution and it is not highly dependent to geometrical conditions. For steady-state simulations, theMultiple Reference Frames (MRF) model is used, for unsteady simulations, the sliding mesh model is adopted.

Surfaces that rotate relatively are defined as "moving wall". Moreover, as they are dependent on the fluid around them and as they rotate, they are defined as "relative to adjacent cell zone" and "rotational motion". Cylinder walls are defined as "stationary wall" and the inlet and outlet are defined as "velocity inlet (7.08m/sec)" and "outflow". Fluid zone in the inner volume is defined as "moving mesh" and 780rpm in x-direction. However, fluid in the outer volume is defined as "velocity inlet (7.08m/sec)". Fig. 4 shows the boundary conditions on entire domain of propeller. In order to give sliding mesh property, the same surfaces in the inner and outer volume families are defined as "interface", and then merged equations are solved iteratively for angular speed of 780rpm. Solution is stopped when changes in solution variables from one iteration to the next is negligible.

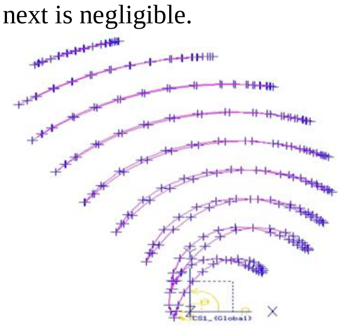

Fig. 1 Points on surface of the blade

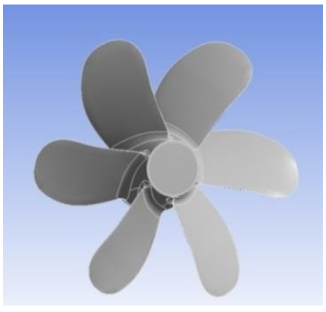

Fig. 2 solid model of propeller

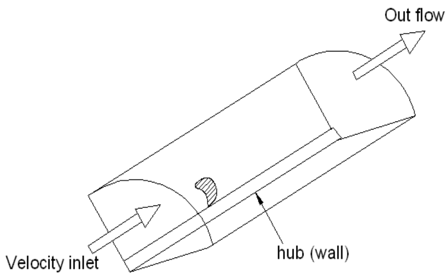

Fig.3 Computational domain and boundary conditions

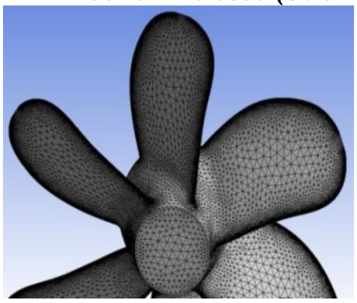

Fig.4 Meshed model of propeller

The same methodology is used for simulations to predict non-cavitation noise of propeller of different propeller rotating speeds of 840 rpm, 900 rpm, 960 rpm at different vehicle speeds of 7.62 m/s, 8.17 m/s, 8.7 m/s respectively.

III. EXPERIMENTAL INVESTIGATION

To validate the predicted noise levels, it was carried out acoustic measurementsfor comparison of the levels of non-cavitatingnoise signatures radiated by this Propeller. The measurements have been carried out at the NSTL Cavitation Tunnel using the ‘‘Acoustic Measurement System (AMS) within the practical limitations and constraints of the set up. The typical model set up is depicted at Fig. 5. Non-cavitating noise measurements have been carried out as per the test programme. The test programme for the above tests evolved within the operating envelope of the tunnel systems are shown in Table 1.The geometrical details of the propeller are as follows:

- Diameter = 389mm; No. of Blades, Z =6;
- BAR= 0.78; P/D = 1.60;
- Hub Ratio = 0.254; Rotation: Left Hand

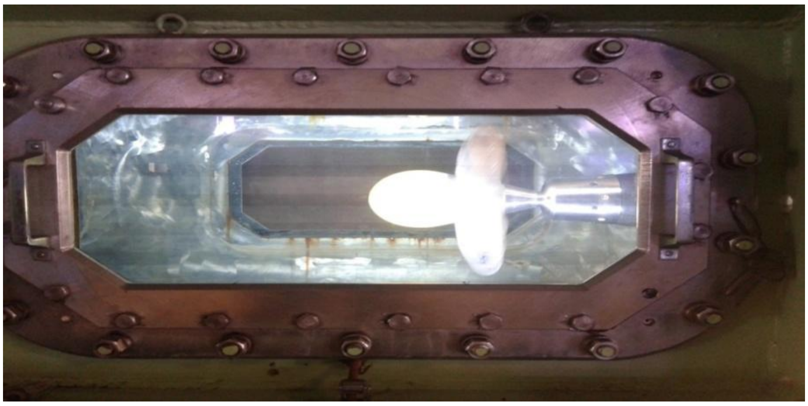

Fig. 5 Propeller in Cavitation Tunnel at NSTL

The salient features of this hydrodynamic test facility are as follows:

- Test section: 1 x l x 6 m
- Motor power: 700 KW DC
- Maximum test section velocity: 15 m/s
- Pressure range (Abs): 0.1-3.0 Kg/cm^2
- Minimum cavitation No.:0.08-37 at Test Section (Control)
- Tunnel background noise: 90 dB (1/3 Octave) ref at 1 μ Pa over 1 KHz - 100 KHz frequency range.

The measurements are repeated in same test conditions for the purpose of examining and establishing consistency and repeatability of results. The results were found to be reasonably consistent. Table 2 shows the final results obtained from the Cavitation Tunnel measurements after deducting the wall correction and normalization for 1m distance from the measured values.

Table1: Operating envelope of the tunnel systems for Non-Cavitating Noise Measurements

Advance ratio (J)	Propeller rpm (n)	Flow Speed V (m/s)	Control Cav. No	Control Pressure(K Pa)	Propeller Cavitation state
1.4	780	7.08	11.1	135	Non-Cavition
1.4	840	7.62	9.53	135	Non-Cavition
1.4	900	8.17	8.3	135	Non-Cavition
1.4	960	8.71	7.15	135	Non-Cavition

Table 2: Experimental results from cavitation tunnel measurements

Frequency (Hz)	SPL (dB//1μpa@1m)			
	780 RPM	840 RPM	900 RPM	960 RPM
2500	125	135	135	115
3150	127	134	134	127
4000	110	129	137	142
5000	102	104	110	115
6300	95	94	96	98
8000	94	88	88	96
10000	98	95	93	97

IV. RESULTS AND DISCUSSION

Basic flow fields of propeller are obtained using a LES solver around the 6-bladed propeller in uniform flow and noise prediction results are presented for non-cavitatingpropeller at different receiver positions. The density and speed of sound in the sea water are 1026 kg/m^3 and1500 m/s, respectively are considered for the present simulations. The reference pressure used for calculating sound pressure level (SPL) is1.0106 μPa. The propeller is assumed to be operated at speeds of 780 rpm, 840 rpm, 900 rpm and 960 rpm at different forward velocities of 7.08 m/s, 7.62 m/s, 8.17 m/s and 8.7 m/s respectively for all non cavitating noise predictions. The receiver position is 1 m in downstream of propeller aligned to the propeller shaft. From these results it is observed that maximum SPL at 1m distance in radial direction of the propeller is 127 dB for 780 rpm, 135 dB for 840 rpm, 137 dB for 900 rpm and 142 dB for 960 rpm. Fig.6 shows the noise prediction graphs for780 rpm of speed and forward velocity of 7.086m/s. Fig. 6 clearly shows that peak sound pressure level values are observed at first blade passing and at the second order harmonic and these are predominated at low frequency only. The basic noise source in propeller is dipolar noise source as generated due to hydrodynamic pressure fluctuation. Simulation results are compared with experimental values obtained from Cavitation Tunnel. Noise spectrums obtained from prediction reasonably match with the noise spectrum obtained from the measurements. Fig. 7 shows the comparison of non-cavitatingnoise levels between predicted and experimental values at 780 rpm. The noise level gradually reduces from 4000 Hz to 10,000 Hz. It clearly shows that average percentage of error between the predicted and experimental values for all propeller speeds is only 8%. This is well below the general average error 10%. The behavior of the propeller observed from measurements is closely matches with prediction. This deviation may be due to contribution from theoretical assumptions which are differing from practical measurements, test conditions and environmental conditions.

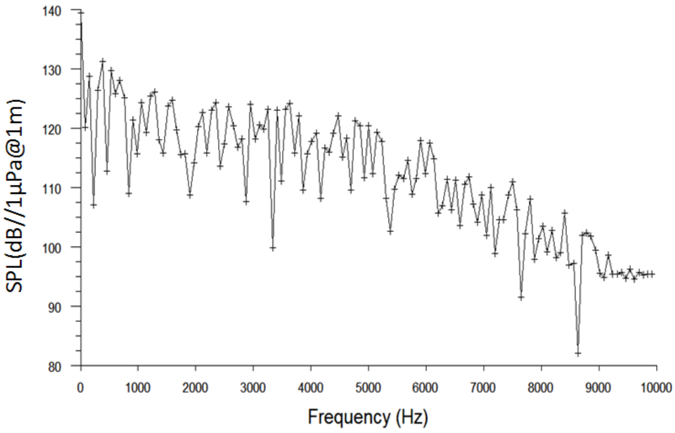

Fig.6 Noise prediction graph at inlet of propeller from simulations at 780rpm

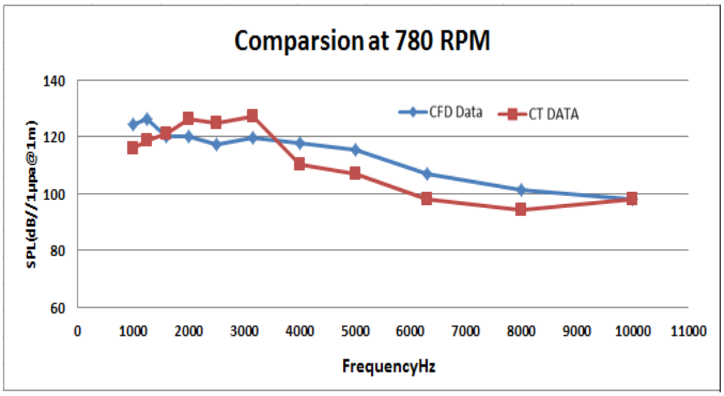

Fig. 7 Comparison of noise from predicted and experiments at 780 rpm

V. CONCLUSIONS

The non-cavitating noise generated by underwater propeller is investigated by both numerical and experimental methods in this study. The non-cavitating turbulent flow around a full scale marine propeller is simulated with the LES (Large Eddy Simulation) approach. For non-cavitationnoise prediction, Ffowcs Williams–Hawkingsequation is adopted in the form proposedby Farassat.Sound pressure levels are predicted and plotted at different receiver positions. From this study, noise prediction methodology has been formulated with LES and FW-H equation. The results are also compared with experiments conducted in cavitation tunnel and it is found good agreement between the numerical and experimental results.

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