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Large Eddy Simulation of Flow around Marine Turbine

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Abstract: The present research investigates Marine Current Turbine (MCT), an exciting proposition for the extraction of tidal and marine current power. CFD simulation is being widely used in the research on MCT. Solution of incompressible unsteady Navier-Stokes (N-S) equations is required in the numerical simulation of flow around MCT. Large Eddy Simulation (LES) has been opted which fully resolves the energetic turbulent flow structures and models only the sub-grid scale turbulence. IB method has been used to enforce the boundary conditions on complex geometry. Due to computational limitations, only a coarse grid LES of the marine turbine for specific operating conditions have been performed. Nevertheless, the results provide insights into the flow structures around the marine turbine. Analysis shows that the effect of vorticity diminishes after 11R from the turbine rotor blade. However, the velocity deficit region remains until the end of the domain used in our simulations which is 10D distance downstream of the rotor blades.

Keywords: *Marine turbine, renewable energy, LES, turbulence, numerical simulation*

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I. INTRODUCTION

Renewable energy has been the focus of research in recent decades due to depleting stock of fossil fuels and ever-increasing demand for energy. The global warming and relevant climate change effects caused by burning of fossil fuels have been a further led to renewed focus on clean and renewable sources of energy such solar, wind, hydro and marine tidal energy. Renewable energy technologies have potential to provide energy security by reducing dependency on fossil fuels, reduce air pollution resulting from burning of fossil fuels and help mitigate greenhouse gases responsible for global warming. Thus, to meet the energy security and obligations on reduction of greenhouse gases mandate by recent international meets, different nations have set their targets for energy from clean renewable energy sources. For example, the European Union has set a baseline target of 20% by 2020 and 40% by 2030 as a share of total energy production. USA has a national renewable target of 20% by 2020. IRENA [1] provides a global energy roadmap (REmap) which shows how the world double the share of renewable energy by 2030 and reduce the carbon emissions by 35%. India has also set its targets for renewable energy share which is an ambitious 40% by 2030. Achievement of this target will help us reduce our dependence on import of fossil fuel, make our cities a lot cleaner by cutting air pollution and help us over-achieve our climate change targets of reduction in CO_2 emissions.

Renewable energy refers to a basket of energy sources as hydro energy, solar energy, wind energy, energy from bio-mass and biogas, marine energy, etc. Of these, technology for the hydropower (both large and small), solar and wind is very well-developed. In contrast to technologies for harnessing marine energy are not that well-developed. These are in various stages of development, commercialization and deployment. Marine energy can be broadly classified in three forms: (i) energy in sea waves, (ii) tidal energy and (iii) energy contained in ocean currents (such as gulf stream). Waves in the ocean are generated due to wind blowing above their large expanses and these waves contain significant quantity of energy. The global technical potential for wave energy

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is estimated to be 500 GW (electrical) assuming a 40% conversion efficiency [2]. Global estimates of tidal energy potential are around 1 TW [3]. For India, the theoretical potential of wave energy and tidal energy are 40 GW and 12 GW respectively [4].

Tidal energy can be harnessed by two approaches: (a) tidal barrage and (b) tidal current. The Marine Current Turbine (MCT), as an exciting proposition for the extraction of tidal and marine current power, has recently gained momentum as a viable technology and is currently the subject of much attention and research. The worlds first commercial tidal stream generator, SeaGen, was located in Strangford Narrows, Northern Ireland and was able to deliver 1.2MW into the UK grid when started. In September 2012 the project was able to produce 5GWh of power, enough to provide power to 1500 households annually. After that different other projects have started among which Sihwa Lake tidal power station, South Korea is the worlds biggest tidal power plant with an output capacity of 254MW. Very good possibilities exist for harnessing tidal energy in India on Gujrat coast and also in Bay of Bengal near Sunderbans delta. As per current estimates of the potential of tidal power generation, India can produce 7000 MW of power in the Gulf of Khambhat in Gujarat, 1200 MW of power in the Gulf of Kutch in Gujarat and about 100 MW of power in the Gangetic delta of Sunderbans in West Bengal. These estimates are very significant, and hence, the Government of India has sanctioned feasibility studies on both east and west coast in collaboration with appropriate nodal agencies of the respective states (West Bengal and Gujrat). At present, SIMEC Atlantis Energy is pursuing a 250MW tidal stream project MUNDRA in the Gulf of Kutch with Gujarat Power Corporation Limited (GPCL).

Research projects are going on about power generation, environmental effect and design of MCT. There are basically two ways of doing research in this area: (a) experimental analysis, and (b) numerical simulation. Although experimental analysis gives reliable results, it requires much effort to model the large-scale problems experimentally. On the other hand, numerical simulations are relatively cheaper both financially and in time and can be easily implemented for different designs. With the development of high-performance computing technology, it is possible to perform a numerical simulation with great accuracy. Therefore, CFD simulation is being widely used in the research on marine current turbines. The present research also represents a step in this direction by the development of a code for LES of marine turbine.

Blunden and Bahaj generated an estimation of available marine energy in Portland Bill (Dorset, UK) by developing a model of Portland Bill itself. They were able to develop a time series of the tidal stream velocity that can be used for future work [5]. Li reviewed the development of tidal current in China. They focused on the available tidal current energy resources, the various energy conversion technologies used in China and also upon various opportunities for the development of tidal current there [6]. Miller et al. explored the site selection for hydrokinetic power resources to know the potential of a source, and various technologies which could be implemented in rural Ghana to provide electricity in rural areas [7]. Vennell presented a method to estimate the potential of tidal current capable of producing power, and provided estimates for New Zealand. While until this point the characteristics of tidal mean flow have been studied and understood, a few information was present on the characteristics of turbulent flow structure. Esteban and Leary in 2012 provided a review of the global potential of wind and ocean energy and estimated that the percentage of electricity that could be produced world-wide was around 7% by 2050 [8]. Later, Milne and colleagues examined the comparatively high frequency instantaneous velocity fields achieved from a tidal energy source site [9]. They analyzed the turbulent velocity fluctuations intensity and characterized the spectral behavior of the turbulent energy with the objective of realistic performance prediction of tidal turbines.

As the most predictable renewable energy source for electric power generations, marine currents can be extracted using various techniques, among which marine current turbines showed very exciting performance. Suitable methodologies are needed to describe their performance, design aspects, desired working conditions and environmental effects (Batten et al. 2006). Primarily two types of marine current turbines are used:

i Horizontal Axis Tidal Turbine (HATT)
ii Vertical Axis Tidal Turbines (VATT)

In the beginning, most of the marine current turbines used to harness the tidal power were horizontal axis turbines. Though most of the characteristics of horizontal axial turbines can be learnt from the technology of wind turbines, there were certain fundamental differences such as different Reynolds number, cavitation problem and free surface effects. Bahaj conducted experiments on a model turbine of diameter 800 mm in a cavitation tunnel and in a towing tank. Power and thrust coefficients of the model turbine have been calculated for different tip speed ratios with various pitch settings in different flow conditions i.e. straight and yawed flow [10]. Their experimental results have been used by various authors to validate their numerical methodologies. Batten et al. developed a numerical model for predicting the hydrodynamic design of marine current turbines which was based on Blade Element Momentum Theory (BEMT). They validated the results of their numerical model using the experimental results. Bahaj have also developed two simulation tools using blade element momentum theory one is SERG-Tidal (an academic in-house code) while other is GH-Tidal Bladed (a commercial code) [10]. They validated and compared the results developed from these two codes with the experimental results and provided satisfactory performances. For numerical simulation of flow through the horizontal marine current turbine, the actuator disc model can be considered as a simple method [11, 12]. Harrison et al. [13] used a simple actuator disc in a commercial CFD code to study the flow through horizontal axis tidal turbines. They showed that initial values of along with the ambient and disc induced turbulence levels were the main factors which affect the far wake structures. Doherty et al. validated the results of FLUENT with laboratory tests, carried out on a scaled horizontal axial tidal three bladed turbine of diameter 0.5 m in a water flume. The water flume had a uniform flow with a velocity of magnitude 1m/s [14].

Khan et al. provided a great review on River Current Energy Conversion System (RCECS) and on the various developments in technologies to harness that energy [15]. Khan et al. [15] wrote a review paper on different hydrokinetic energy conversion technologies. They focused mainly on certain aspects of hydrokinetic systems such as duct enlargement, general trends in the design of systems and placement methods. They have also ventured on the classification and performance of the horizontal and vertical axis turbines. It was found that the vertical turbines were designed for either near surface mounting or floating arrangements and axial turbine were preferred for being placed at the bottom of the channel. Guney and Kaygusuz [16] and Lago et al. [17] provided overview on various types and techniques of hydrokinetic turbines. They showed that the vertical axis turbines generally require some exciting and starting mechanism, axial turbine systems are the best suited for harvesting tidal currents. They also provide information about different capacities of turbines at different stream velocities

Anyi and Kirke [18] deal with small axial hydrokinetic turbines used in remote communities which are off the grid power supply. These small axial turbines are either suspended from river banks or jetties using pivot arms or mounted on pontoons and are capable of extracting 1 kW to 2kW of power sufficient for suitable homes. However, the major problem was the excessive work associated in removing debris and frequent power cuts due to this and furling resulted in impediment in accepting the hydrokinetic system in remote communities. In order to overcome these issues, use of a system with swept-back blades that can shed the debris automatically without requiring to lift the turbine out of the water and use of high-speed axial flow turbines with higher rate of efficiency are suggested.

Li and Calisal [19] studied the three-dimensional effects of a vertical axis tidal turbine using the vortex method. Using their numerical method results they suggested that when the height of the vertical tidal turbine is more than its radius, three dimensional effects became in significant. Along with the three-dimensional effects, they also quantify arms effects using an analytical derivation of a relation between arm effects and tip speed ratio. A new system for collecting the river and tidal current energy has been designed by Amelio et al. [20] to provide a simple, cost-efficient, high performance kinetic turbine system. In the system the kinetic turbine immersed inside the water currents while being held by a steel cable attached to the shore and the turbine was kept at equilibrium by the help of a central deflector. This paper also described design parameters of an installation in Punta Pezzo, Italy.

Savonius turbine is a traditional turbine which shows many benefits like self-start ability, structural simplicity, bi-directional rotational ability, relatively low operating speed and also has a lower environmental impact [21]. But it shows comparatively less efficiency than the other marine current turbines. Hassanzadeh et al. [21] developed a new design concept for the Savonius turbine named Reza Turbine and studied the pressure distribution and flow using unsteady RANS equations. A numerical method developed by Gaden and Bibeau [22] was focused on investigating the effects of using diffusers in order to enhance the performance of hydro turbines. They modelled the turbine as a momentum source region in order to simplify the problem and they showed that the use of diffuser with a turbine generated of 3.1 times more power compared to those turbines with no diffuser.

The main objective of this paper is the LES of the turbulent flow around complex geometries. Particular application problem was flow around the marine current turbine. Most of the simulation tools developed for marine current turbine flows have been based on blade element method [10, 23, 24] which models the presence of turbine blades. In contrast, we have developed the LES code which solves the flow in complete geometry. Geometric complexity resulting from moving curved blades has been accounted for using the immersed boundary method.

LES is based on explicit time integration. From the assessment of different iterative techniques for solution of pressure Poisson equation, the fictitious domain multigrid preconditioner in BiCGSTAB method performs the best for non-uniform grids. Therefore, the technique used for simulation of the flow around the marine current turbine is LES of N-S equation using the IBM combined with the pressure Poisson solver based on the BiCGSTAB method with the fictitious domain multigrid preconditioner. We have tested and validated our code extensively on test problems as presented in previous chapters. However, due to severe computational limitations (access to only a small HPC cluster with a maximum of 96 cores available for a parallel job at a time), we have been able to perform only a coarse grid LES of the marine turbine for specific operating conditions. Nevertheless, the results would provide a demonstration of the capabilities of our LES code, and also provide some insights into the flow structures around the marine turbine.

II. COMPUTATIONAL DOMAIN

The turbulent flow structures around a marine current turbine have been studied here. The turbine geometry used here is similar to that used by [25] (Fig. 1). The size of the computational domain is approximately 5.5D along height (vertical direction) and width (spanwise direction), and 12D along the length (streamwise direction). The diameter D of the turbine here is chosen as 800 mm similar to that of [10]. We are here interested in flow structure and transport of wake characteristics. The boundary conditions along the vertical and spanwise direction are imposed as free-slip walls while along streamwise direction inflow boundary condition with a flow speed of 1.72 m/s and convective outflow boundary condition with zero velocity gradient has been used. The dimensions of the rectangular computational domain are selected to be $[-2.3,4]\times[-2.3,2.3]\times[-2.3,2.3]$ in x, y, z directions respectively. The origin of the Cartesian coordinates is assumed to be located at the center of the plane passing through the hub near the location of the attachment of the blades. The computational domain is discretized using a Cartesian rectangular non-uniform $1024\times 768\times 768$ grid. The decimal point in the range of domain is due to the use of stretching factor 1.05. A uniform grid has been taken immediately around the turbine, and the grid is stretched thereafter along three dimensions toward the boundaries. The computation on the full domain is run continuously on HPC cluster, available in the CFD lab of IIT Roorkee, using 6 nodes each having 16 cores.

Fig. 1. Geometry of the model marine turbine. Triangulated patches have been used in IBM for representation of the complex and moving boundary surface of the turbine.

Blackmore et al. [26] suggested that in marine current turbine flow simulation, specifying a turbulent inlet condition is ideal since it affects the velocity field in far wake area. However, this requires detailed time-dependent flow field such a tidal fluid velocity, depth of the water, turbulent flow details and detail geometry of a large region.

Since very little measurement data are available, the flow is assumed to have a uniform free stream velocity of 1.72 m/s. We first generate a solution using a tip speed ratio TSR = 4 for up to 100 rotations. The velocity and pressure fields of this simulation are used as the starting point for our simulation of the marine current turbine flow field for a TSR value of 6.

III. FLOW ANALYSIS OF MARINE CURRENT TURBINE

Fig. 2 shows the contours of the stream-wise flow velocity at different streamwise planes around the turbine. In Fig. 3, we have tried to depict the velocity deficit caused due to the extraction of kinetic energy from the fluid. Fig. 2 and 3 show the flow field on planes passing through two different locations: one at the center of the turbine hub, and another at the tip of the blade. This has been done in order to see the clearer picture of the velocity field. Fig. 2 shows clearly the velocity of the free stream decreases before it hits the turbine hub. Here, we can see the velocity deficits occur majorly from the root and tip of the turbine blade. Fig. 3 shows the velocity deficit remains until 9.5D. The largest velocity deficit occurs at the section just after the turbine blade. Due to the shortage in available computing resources, we could not increase the size of our computational domain beyond 12D to clarify the development of the velocity field further downstream the turbine.

Next important flow parameter is the formation of vortical structures in the wake. Vorticity is created when the fluid hits the hub and blades of the turbine. The intensity of the vorticity decreases drastically after 1D distance away from the turbine blade (Fig. 4). As discussed by [24], the turbine wake formation can be divided into three phases: shedding, mixing and fully turbulent. Here it can be observed from Fig. 4 that after the vorticity is shed from the blades, the stable vortices last only 1-1.5R away from the rotor blade and the flow became fully turbulent after that. Fig. 5 shows the vorticity formation and transport in streamwise direction at two different positions: one at a section cut at the center of the hub, and another one at the tip of the rotor blade. Fig. 6 show the intensity of the vorticity magnitudes at various cross-sectional plane starting from the entry of the domain until the end of the flow domain. These figures show the varying intensity of the vortices from being maximum at the turbine rotor blade to minimum at the end of the domain. It can be noticed that the intensity of the vorticity magnitude is very less after 11R distance away from the rotor blade since its maximum is less than that at the tip of the hub.

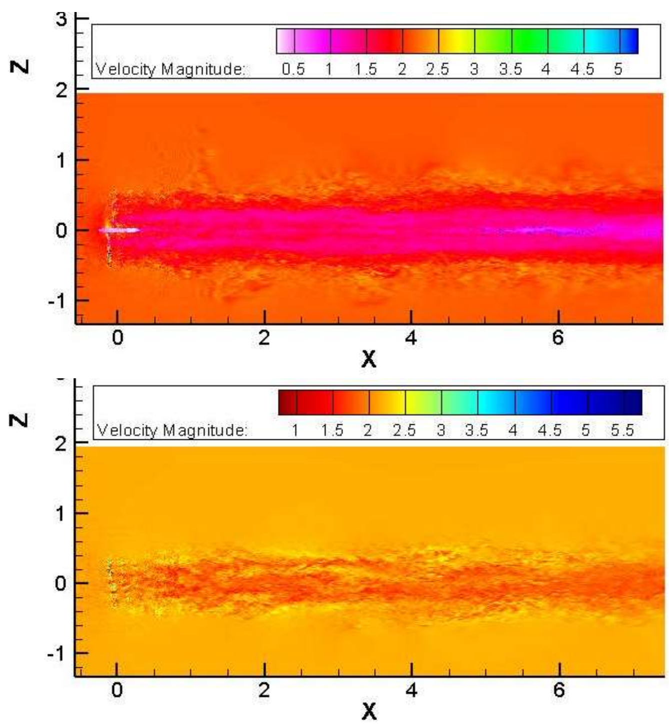

Fig. 2. Velocity magnitude along the streamwise planes at two locations: (a) At the center of the turbine hub, and (b) At the blade tip.

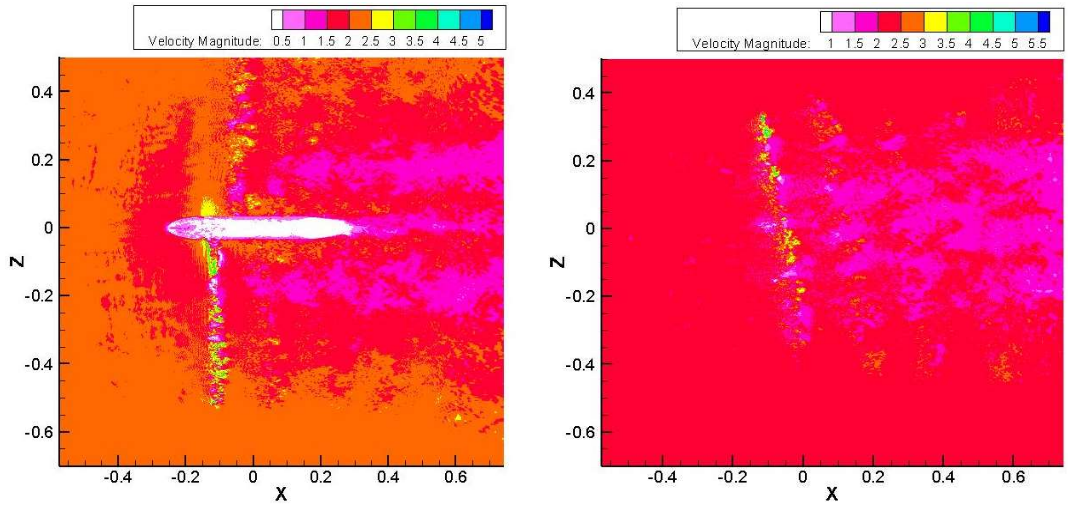

Fig. 3. Velocity deficit regions at two locations: (a) At center of turbine hub (b) At blade tip.

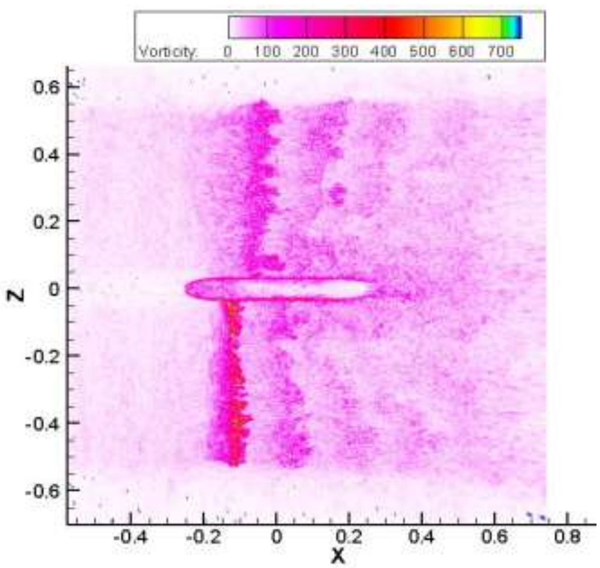

Fig. 4. Eddy formation and dissipation around the turbine hub and blades as indicated by vorticity magnitude.

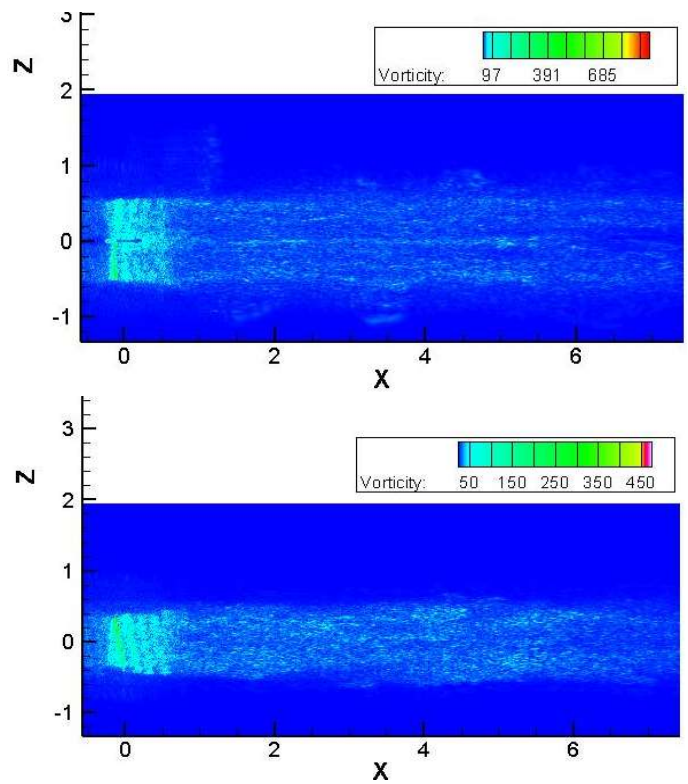

Fig. 5. Vorticity magnitude variation along the stream wise flow direction. (a) At the center of the turbine hub, and (b) At the blade tip.

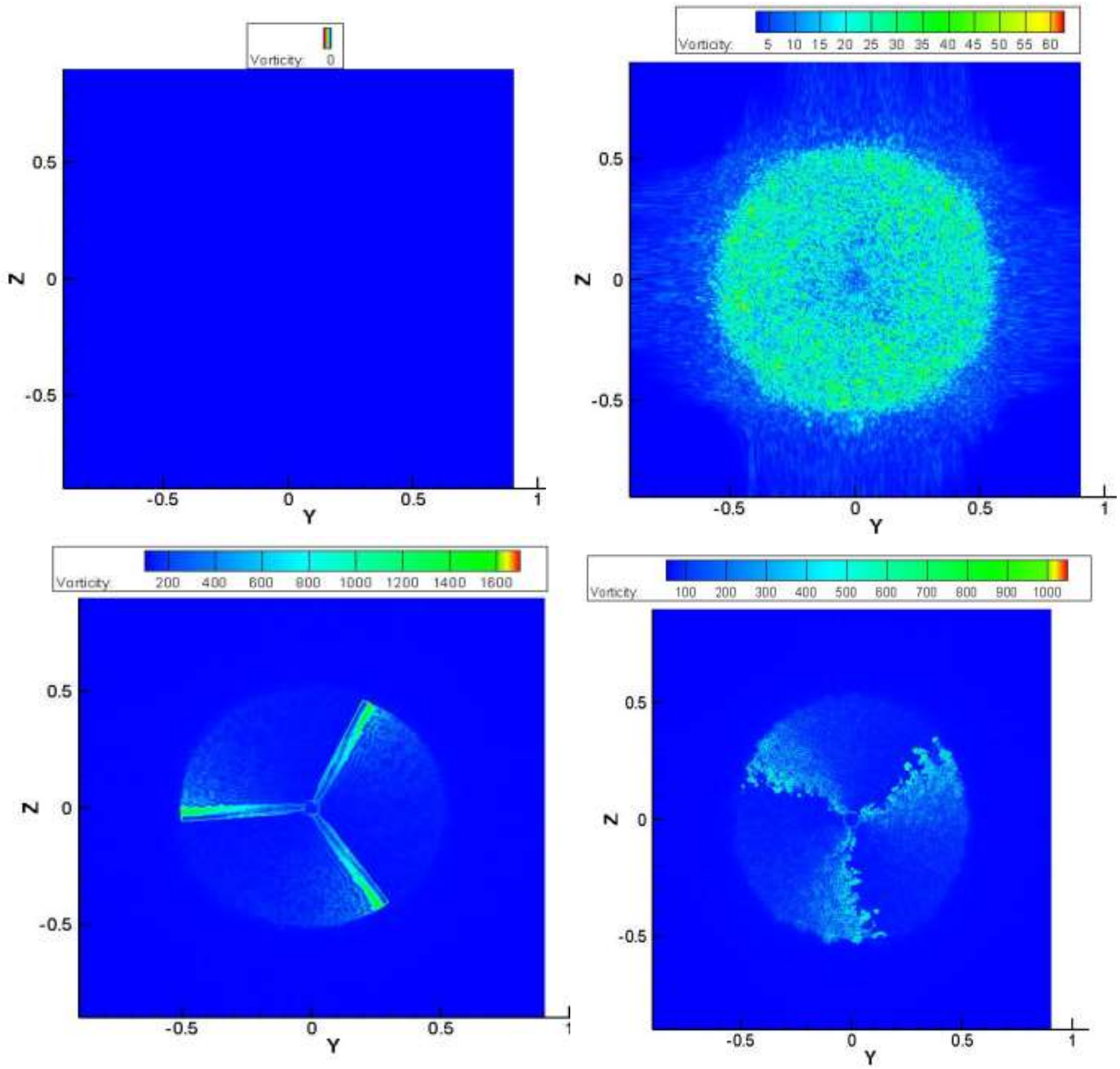

Fig. 6. Vorticity magnitude at different cross-sectional planes at different locations upstream and close to the rotor blades. (a) At the entry of the domain (b) At tip of the hub (c) At rotor blade (d) Just after rotor blade

IV. CONCLUSION AND RECOMMENDATIONS

The flow around a marine current turbine is simulated, and its flow structures are analyzed. The Navier-Stokes equation is solved using the Adams-Bashforth method as time advancing scheme and the pressure Poisson equation arise during the numerical simulation is solved using the BiCGSTAB method with fictitious domain multigrid preconditioner. Major flow parameters such as velocity and vorticity at different sections of the flow domain has been analyzed. It is observed that the effect of vorticity diminishes after 11R from the turbine rotor blade. However, the velocity deficit region remains till the end of the domain used here which is 10D distance away from the rotor blade. In future, further detailed investigations in the field of MCT are encouraged.

Declaration of conflicting interests

Th authors confirm that it is original work which is not published elsewhere and there are no financial or non-financial conflicts in this work.

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