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Computational Fluid Dynamics Simulations of Ship Airwake with a Hovering Helicopter Rotor

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Abstract: Computational Fluid Dynamic simulations of ship airwake are performed together with an actuator disk model for a rotor model hovering over the flight deck. The flow around Simple Frigate Shape 2 (SFS2) is computed in steady-state and unsteady conditions by solving RANS and hybrid RANS/LES equations. The unstructured grid is generated for the ship geometry. Also, an actuator disk is added into the model to investigate downwash effect of rotor on ship airwake and interaction of rotor and ship airwake.

Keywords: Ship Airwake, Computational Fluid Dynamics (CFD), Helicopter Rotor, Actuator Disk Model

1 Introduction

The helicopter ship operations such as launch and recovery are one of the most challenging operations for the pilots. The pilot should overcome bad weather conditions, airwake of the ship due to superstructures, visibility problems and moving flight deck during hovering over or landing on the flight deck. The most dangerous problem occurs because of ship airwake, which is a highly turbulent, three dimensional, vortical flow with large regions of separation behind the superstructure of the ship and over the flight deck. In order to make helicopter-shipboard operations safe, The Safe Helicopter Operating Limits (SHOLs) should be determined for each helicopter-ship combination. SHOLs are generally expressed by wind-over-the deck envelopes, which show allowable wind conditions in terms of azimuth angle and speed for a given helicopter ship combination. These envelopes can be obtained by either experimentally or computationally. In the experiments, full scale tests or model scale wind tunnel tests are performed. It is hard to obtain WOD envelopes by full scale tests because they are expensive, time consuming and unsafe. Moreover, results can vary according to the pilot's evaluation. Also, model scale wind tunnel tests are costly and time consuming, and they can remain weak to create the complexity of real flow field. On the other hand, numerical methods are safer, cheaper and easier to control. By using suitable models, the results can simulate the real situation.

When simulating the complexity of the airwake, some technical challenges may occur. Modeling of the ship is difficult due to its complex geometry including towers, antennae, radar dishes, exhaust stacks. Also, moving flight deck which is due to sea waves can alter the characteristics of the flow field. Therefore, modeling sea waves and ship motion is important. Moreover, interaction between ship and helicopter's rotor and fuselage must be taken into account, which makes the flow more complex. In addition to these, the results can be affected by application of atmospheric boundary layer and atmospheric turbulence.

In this paper, the flow over Simple Frigate Shape 2 (SFS2) is simulated by using Computational Fluid Dynamics (CFD). In order to investigate the effect of the inclined flight deck due to ship motion, 10 degree roll is given to SFS2. Also, by using actuator disk model, the effect of the rotor on the ship airwake is studied.

The detailed summary of the studies, performed before 2005 on ship airwake and dynamic interface, is given by Sezer-Uzol et al [1]. Review on the previous studies both experimental and computational, performed after 2005 on ship airwake and dynamic interface, are summarized in the next subsections 1.1 and 1.2. Also, a short review of the literature on ship motion is presented in the subsection 1.3. The CFD simulation details are presented in the section 2 and the results of these computations are given in the section 3. Finally, conclusion and future works are discussed in the section 4.

1.1 Previous Studies on Ship Airwake

In order to investigate and understand turbulent, unsteady characteristics of ship airwake, many studies on various ship models were conducted computationally and experimentally. As mentioned above, this part gives only the recent studies on ship airwake, since the studies before 2005 were presented previously.

The recent experimental studies include wind tunnel tests on SFS [2], SFS2 [3, 4], and USNA YP676 [5] and LHA [6], and full scale tests on SFS [2] and USNA YP676 [7]. These tests provide flow topology on the surface and velocity data including mean velocities and turbulence intensities. Also, the interaction between the ship air wake and the helicopter was studied by Forrest [8] and Nacakli [9] with model scales of Merlin AW-101 and SRF and a simplified 1/50 scale frigate waterline model and traverse mounted powered rotor respectively.

The Computational Fluid Dynamic (CFD) analyses were performed on different ship models with different numerical methods. Many researchers focused on only analysis of air wake. In 2006, Sezer-Uzol et al. [1] investigated the flow around a Landing Helicopter Assault (LHA) ship and a Landing Platform Dock-17 (LPD-17) ship by using CFD solver PUMA2 for inviscid flow with slip wall boundary conditions for the ship and sea surface. LHA is also verified with experimental data in 2012 [10] by using three different grids including prismatic layer grid and it is shown that the prismatic layers do not affect the results. In 2008, Syms studied both SFS and SFS2 geometries by using Lattice- Boltzman method [11]. Various spatial discretization schemes on SFS were discussed by He et al. in 2014 [12]. Forrest et al. validated their computational data of SFS2 with experimental results and compute the flow over T23 ship by using hybrid turbulence model DES with SST k-omega [3]. They stated that application of Atmospheric Boundary Layer on computations can increase the accuracy. Another study on SFS2 was conducted by Quon et al. in order to assess the ability of URANS and URANS/Vorticity Transport hybrid computational methodology to capture airwake characteristics [4]. Three flow conditions on SFS2 was also investigated by Zhang et al. using unsteady flow solver Cobalt in order to use the results in a work of helicopter-ship interaction [13]. Muijden et al. solve the flow over SFSN (SFS with modified bow by National Aerospace Laboratory) and LPD2 by steady state with RANS and unsteady with hybrid RANS/LES turbulence model, and compare results with experimental data [14]. Implicit large eddy simulation was validated on two different Royal Navy ships; T23 and Wave Class AO by Thornber et al by comparing results with both wind tunnel and full-scale tests [15]. In 2012, Snyder et al. solve flow over USPN-76 using Monotone Integrated Large Eddy Simulation for 6 different WOD angles [7].

In addition to the airwake computations, there have been several computational studies on ship airwake/helicopter rotor. Hodge et al used the time-accurate ship airwake data obtained on SFS2, in order to observe unsteady aerodynamic load on helicopter in 2009 [16]. In this study, ship motion effect on pilot workload was also studied in the flight simulator. In 2014, the effect of the ship size was investigated by using DES turbulence model and the obtained data was extracted to perform an offline flight mechanics operating analysis of the SH60B rotor response [17].

1.2 Previous Studies on Dynamic Interface

The helicopter and ship interaction has been an important topic for researchers. This is mainly due to investigating pilot's response and workload during helicopter's shipboard operations, determining the safe WOD angles, generating safe flight trajectories for helicopters and developing flight simulators for training pilots and engineering. These studies are conducted on different classes of ships and helicopters such as SFS2 [18, 4] with SH-60B [19, 17] and Lynx-like helicopter [8], LHA with UH-60A [20]. Additionally, interactions of DDG-81 class ship with H-60 actuator disk model [43], CPF ship with Shipborne Sea King Helicopter, and actuator disk model [21], Type 23 Frigate and Wave class auxiliary oiler with SH-60B [22], DDG-88 ship model with SH-60B [23] helicopter/ship combinations were investigated.

The ship airwake obtained from coupled studies with rotor wake have very different flow characteristics compared to the isolated ship simulations [24]. In 2005, Lee et al. studied DI between LHA and UH-60A by using PUMA2 and GENHEL [25, 26, 27]. By using the same code and flight dynamics simulation model, Alpman and Long also investigated interaction between LHA and UH60-B [20], and they compared fully coupled results with one way coupled and no-coupling case in 2007. As a result, it was stated that the airwake is influenced by the rotor wake and this effect gets powerful as helicopter moves closer to ground and hangar structure. In 2009, the study with the same helicopter/ship combination concluded in that trailing edge flaps can be useful for shipboard gust alleviation by Montanye et al. [28]. Downwash effect of H-60 rotor on DDG-81 class ship was investigated by Schau et al in 2014 [29] and it was stated that airwake energy increases with downwash in one order of magnitude. The steady-state calculations with actuator disk model and CPF ship model were observed to be sufficient to understand the importance of the coupling effects by Crozon et al in 2014 [21]. They also performed unsteady RANS simulations using Sea King helicopter rotor blades. The SHOL diagrams for the FLIGHTLAB model of SH-60B Seahawk helicopter over the deck of a Type 23 frigate and a Wave class auxiliary oiler were determined by Forrest et al [22]. In this study, pilot's ratings and comments were also mentioned. SH-60B was also integrated on the study of SFS2 ship airwake at 2 different WOD angles with the various helicopter locations [19]. Another ship-helicopter DI study of Type 23 frigate was conducted by using Merlin helicopter simulator as a part of project SAIF [30]. When determining SHOL for a helicopter-ship combination, small-scale geometric features should be also taken into account according to Forrest et al [8]. They found that relatively small-scale geometric features can alter the characteristics of the flow field even though they may not affect the pilot ratings. In 2007, Gaonkar developed a complete stochastic model for ship airwake [31]. In this paper, complete stochastic was referred to autospectral densities of all velocity components and cross-spectral densities of any combination of velocity components at two arbitrarily chosen points. Stochastic model for airwake instead of the CFD was preferred over DDG-81 model ship by Sparbanie et al. in 2009 [32] and Rigsby et al in 2011 [33]. Geiger et al. studied on the development of a flight control design to compensate the airwake load on S-92 class over a DDG-81 shipboard environment [34]. In 2011, He et al. developed a simulation and control tool for a helicopter-ship dynamic interface [35]. Horn et al. developed an on-line algorithm to identify the airwake disturbance rotors by using linear filters on unsteady disturbance during real time simulations [36]. Schafer et al. also carried out a work on the development of methodology of the identification of ship airwake gust disturbance in order to use this data on DI simulations later [37].

The effect of the hangar edge on the helicopter/ship DI was also investigated over SFS2 [18]. While the modifications decreasing airwake turbulence does not necessarily decrease the pilot workload, the relation between the modifications increasing the effect of airwake turbulence and the pilot workload is more obvious.

1.3 Previous Studies on Ship Motion

Also, moving platform is another difficulty for helicopters' shipboard operations. The airwake around the ship's superstructure is affected by moving flight deck due to sea waves. This creates more dangerous environment for helicopters' landing and hovering.

The ships floating over sea are under the influence of 6 degree of freedom rigid body motion. These are translational motions; heave, sway and surge, and rotational motions; pitch, roll and yaw. Heave, pitch and roll occur due to sea waves which is the most important factor of the unintended ship motion. Sea waves can be classified as regular and irregular waves. While the regular waves are harmonic, the irregular ones are obtained by superposition of sinusoidal waves [38]. For example, Soneson and Horn used the sum of sine waves to illustrate the motion of TMV-114 Fast Ferry [5].

In the literature, there are many studies [5, 39, 40, 41, 42, 43, 44, 45, 46, 47] investigating the ship response to sea waves for different sea states. In 2011, a computer program WISH which uses time-domain Rankine panel method and solves ship response to linear and nonlinear sea waves was developed by Kim et al [42]. Like the panel methods, the CFD also gives valid results for fully nonlinear analysis [41]. The volume of fluid (VOF) method is used in order to model the sea waves in the CFD analysis of ship motion [43]. Lin and Kuang developed a fully nonlinear dynamic numerical model for X craft catamaran with a fixed heading, which means the yaw, surge and sway motions are not investigated [44]. Carrica et al. studied heave and pitch motions by using dynamic overset grids and their computational results showed excellent agreement with experimental data [48]. Tezdogan et al. again used overset grids to model the computational domain which was constructed for calculation of the ship response to sea waves by using URANS equations [47]. In 2005, Weymouth et al. compared steady-state and unsteady RANS simulations of heave and pitch motions and investigated first and second harmonic amplitudes of motions [49]. Mousaviraad conducted a comprehensive study including harmonic waves and windy conditions effects on ship resistance, maneuvering, seakeeping and controllability [50]. In this study, URANS turbulence model and single-phase level-set free surface model were preferred. In 2013, Simonsen et al. conducted experimental and computational studies over KCS container to analyze the heave and pitch motions during regular waves [46].

In 2006, a control system was developed for unmanned aerial vehicle's shipboard operations using motion data of FFG Sidney and ANZAC frigate under the influence of sea waves [51]. There were given 10 different sea states, from 0 to 9, describing calm and phenomenal water. It was stated that frigates perform heave between +2.5 m and -2.5 m, pitch between +4.8o and -4.8o and roll between +26.5o and -26.5o for sea state 6 which corresponds to very rough wave conditions. Ueng et al. simulated ship motions for three different classes; warship, craft and fishing boat in 2008 [52]. Sea waves are also influenced by the ship rigid body; therefore there is a coupling effect on ship motions. In the literature, studies investigating this coupling effect also exist [42].

2 CFD Simulations

The ship airwake is investigated on SFS2 in four different cases: horizontal (un-inclined) ship, inclined ship by 10 degree roll, horizontal (un-inclined) ship with rotor and inclined ship by 10 degree roll with rotor. Computations are conducted with freestream velocity of 30 knots (15.43 m/s) and WOD angle of 0 degree. SFS2 is an extended version of Simple Frigate Shape (SFS) with a pointed bow. In several ship airwake studies [3, 4], this geometry is used as the ship model. The flight deck is located behind the hangar structure. Although it is a relatively simple geometry to compute, it gives realistic results.

The rotor of Sikorsky S-76 helicopter is used as a rotor model in this study, which is a four-bladed, fully articulated rotor system. It is one of the most tested rotor systems with SC1095 airfoils; therefore, there is a very large database available in the literature [53].

The computations are conducted using CFD++, which is commercial CFD software. It provides users to generate steady-state and unsteady simulations for compressible and incompressible, laminar and turbulent flows in a large range of speed regimes including low speeds through subsonic, transonic, supersonic and hypersonic speeds. There are several turbulent models (RANS, hybrid, LES) available. Also, it allows very complex geometries to be solved by using any kind of cell types and all grids such as structured, unstructured, hybrid and overset. In addition, application of physics sources such as helicopter rotor is already included.

2.1 Unstructured Grid

The unstructured grids are used for full scale SFS2 geometry due to their capability of resolving the complex structures and simplicity to generate. The grids are generated by using Pointwise grid generation software. A fairly uniform grid surface on the ship is generated because the time step is determined according to the minimum cell size by using explicit time scheme. However, smaller triangular cells are preferred on the surface corresponding to flight deck in order to get finer grids in the region above the deck. In the Figure 1, the computational domain can be seen. The detailed mesh of the ship surface is given in the Figure 2.

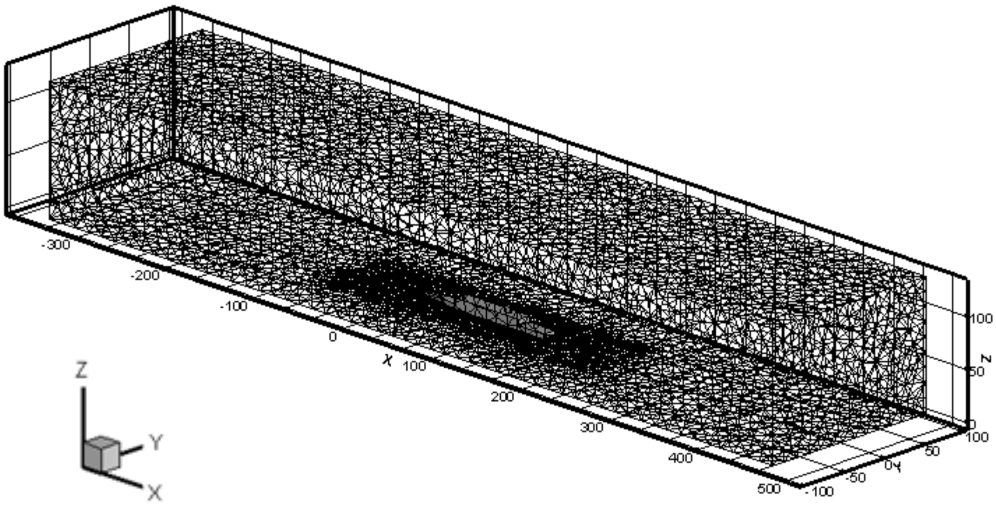


Figure 1: Computational domain

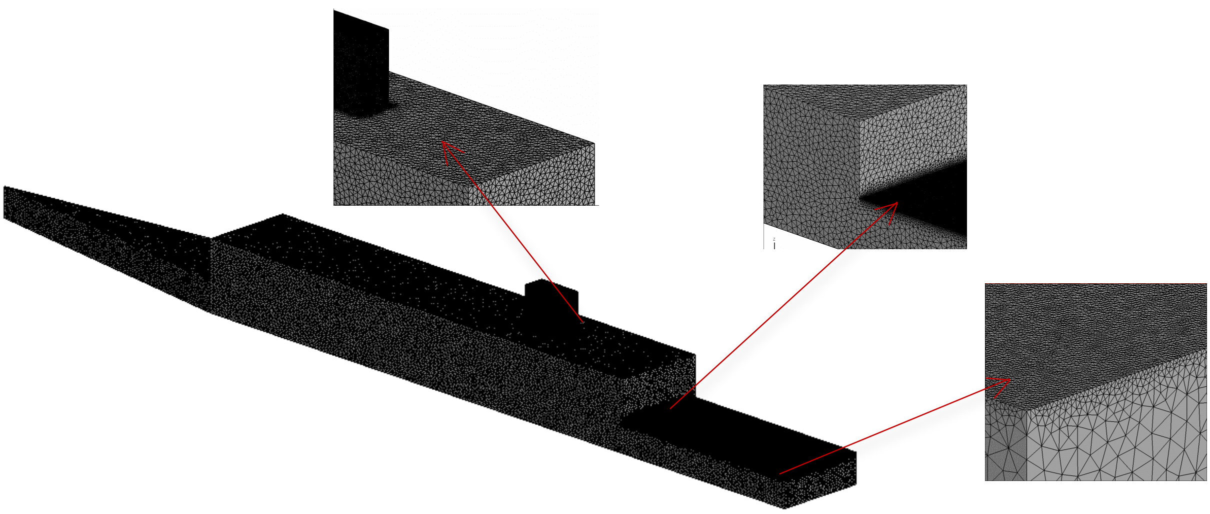


Figure 2: Mesh of the SFS2 standard ship model (horizontal)

The full scale SFS2 geometry used in the simulations has length of 140 m, and width of approximately 14 m. The flight deck is 4.5 m above the sea level and the height of the hangar structure is approximately 11 m [3, 4]. The domain extends 2.5 times of the ship length behind and in front the ship, while the side walls of the outer domain lie between 7 times of the ship width from the centerline. The computational domain has 1028 K tetrahedral grid cells. The bottom surface of the domain refers to the sea surface. The upper surface is approximately 12 times the hangar height above the bottom surface.

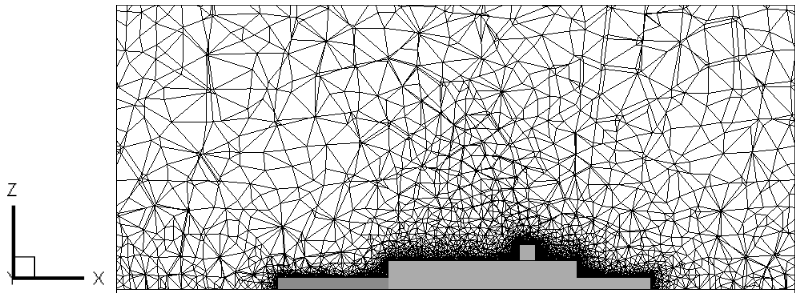


Figure 3: Mesh view on the centerline slice

Inclined flight deck is an important factor for the helicopter's shipboard operations. Therefore, the ship model is given a roll angle of 10 degree about the x axis. On the ship surface and other five surfaces of the domain, the same grid size as previous computations is given. The new computational domain can be seen in 3-D view in Figure 4. The new computational domain contains approximately 778 K grid cells. The back view is given with comparison to the standard ship in Figure 5.

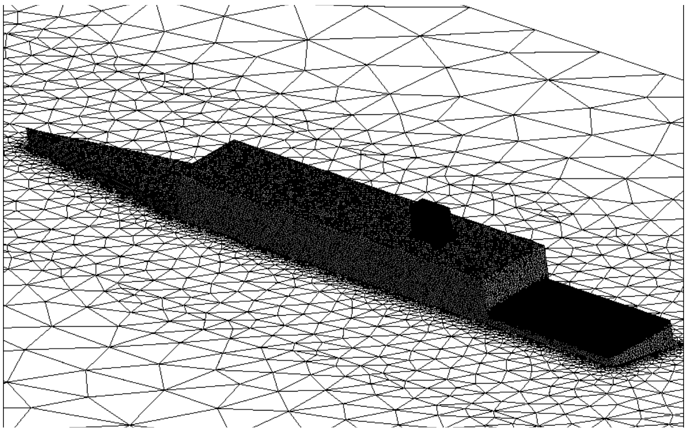
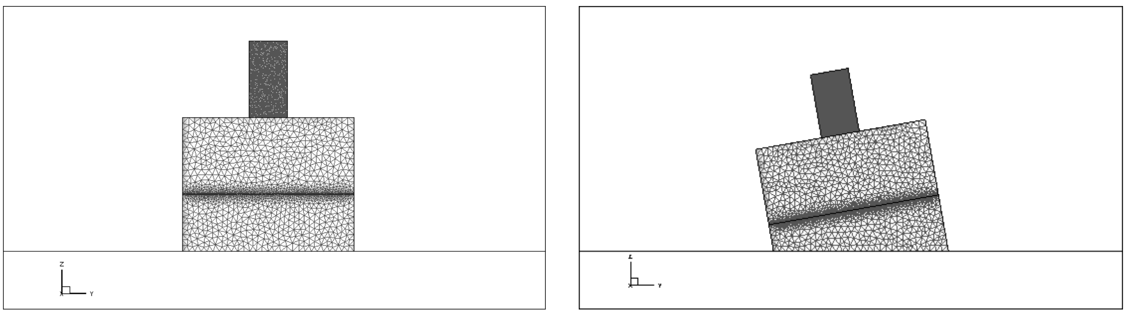


Figure 4: Mesh of the inclined SFS2 ship model



(a) (b)

Figure 5: a) Standard (horizontal) SFS2 ship model b) Inclined SFS2 ship model

In order to investigate the rotor downwash effect on ship airwake, as the importance of the interactions is mentioned in the previous sections, an actuator disk model is added to the domain. The position of the disk in the first combination (horizontal ship) is chosen as mid-deck at 11 m above the waterline. The location of the rotor disk is kept unchanged for the other combination (inclined ship). While the domain with disk on the plane ship has 3030 K number of grid cells, the combination of inclined ship and disk geometry contains 2267 K grid cells. The unstructured meshes are shown for two combinations in Figure 6 and 7, respectively.

In all computations, the slip boundary condition is used for the ship's surface (like Euler simulations although RANS or RANS/LES are solved). Slip condition is also used for the sea surface which is bottom surface of the domain. The characteristic-based farfield boundary condition is used on the outer domains, hereby any reflection is avoided from side walls.

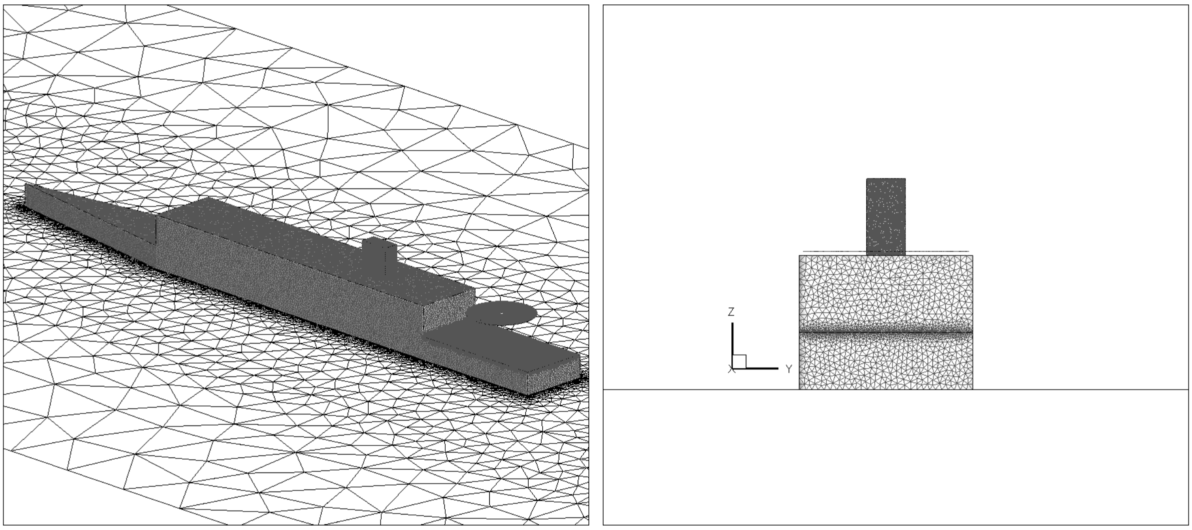


Figure 6: Horizontal SFS2 ship model with rotor disk

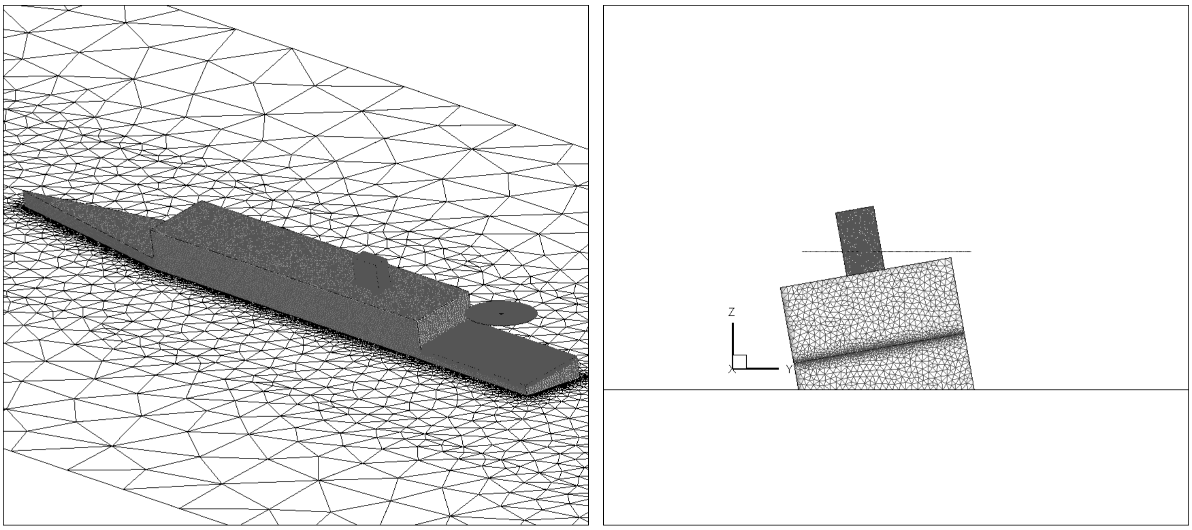


Figure 7: Inclined SFS2 ship model with rotor disk

2.2 Parallel Computing

The computations were performed by using the Poyraz HPC Cluster at the Dept of Aerospace Engineering/RÜZGEM in METU. Poyraz HPC Cluster has eight nodes, each with four AMD Opteron

6276 2.3 GHz central processing units (CPU) which has sixteen cores and 32 MB RAM per CPU, 256 GB DDR3, 1333 MHz 8 GB dual in-line memory module (DIMM) and it is using 10 gigabit ethernet (GBE) connection with total 512 cores, 2 TB memory and 20 TB storage capacity. The operating system is Centos/Scientific Linux. The computations for this study are performed on 16 or 64 processors.

3 CFD Results

The CFD simulations are performed for four cases, the ships that are horizontal and inclined and the ships with rotor model that are again horizontal and inclined. The results are presented and discussed below.

3.1 Results for Standard Ship and Validations

In this study, ship airwake over SFS2 is investigated by using RANS and hybrid RANS-LES turbulence models and they are compared.

First, the steady-state computations are performed with different turbulence models; realizable k-epsilon and hybrid RANS/LES. Steady-state realizable k-epsilon shows good agreement with previous experimental findings in terms of flow pattern on the ship surface. In Figure 8, the surface flow topology obtained by steady-state realizable k epsilon model is shown with comparison to the experiment by Mora [2].

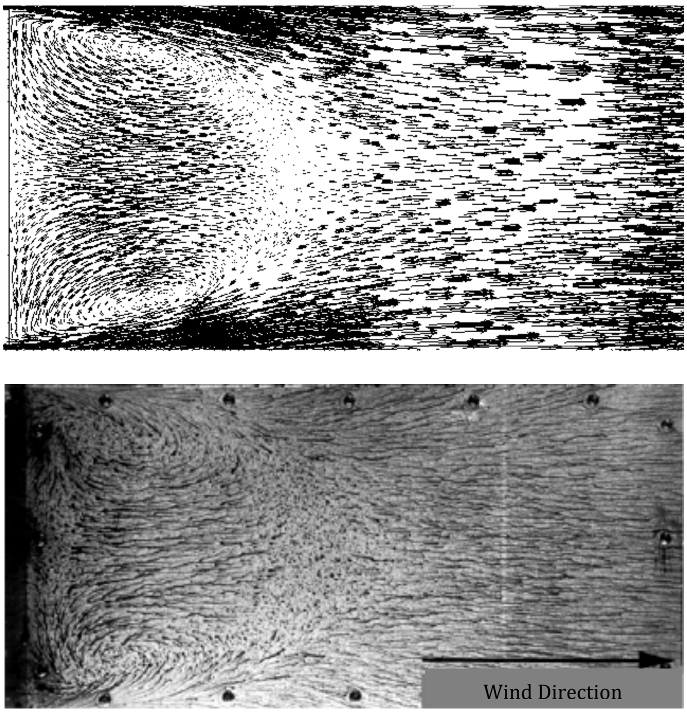


Figure 8: Comparison of steady-state RANS simulation results (top) with SFS2 experiment (bottom)

In Figure 9, flow field at half hangar height and at centerline are given. Also, steady-state hybrid turbulence model calculations are conducted. It gives promising results when comparing to wind tunnel tests in Figure 10 and 11. The wind tunnel tests were conducted by Mora in 2014 [2] with 20 m/s freestream velocity. By comparing contour plots, non-dimensional velocity magnitudes show good agreements. Also, locations of the horseshoe vortex structure are similar.

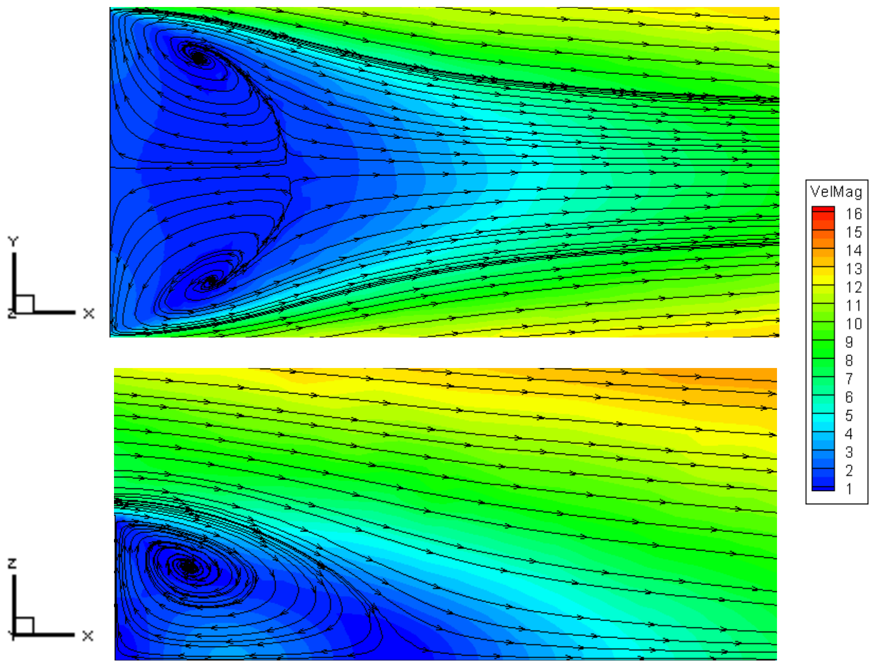


Figure 9: Streamlines on the horizontal slice at half hangar height (top) and at vertical slice along centerline (bottom) with steady-state RANS for horizontal ship

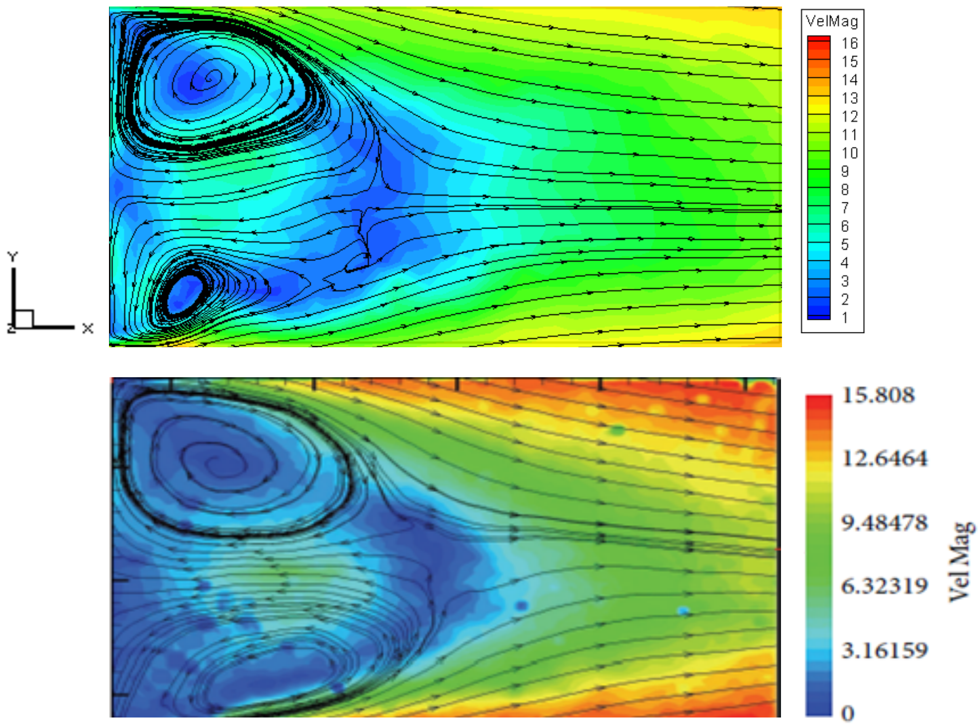


Figure 10: Comparison of streamlines on the horizontal slice at half hangar height with hybrid RANS/LES (top) and experimental data (bottom) for horizontal ship

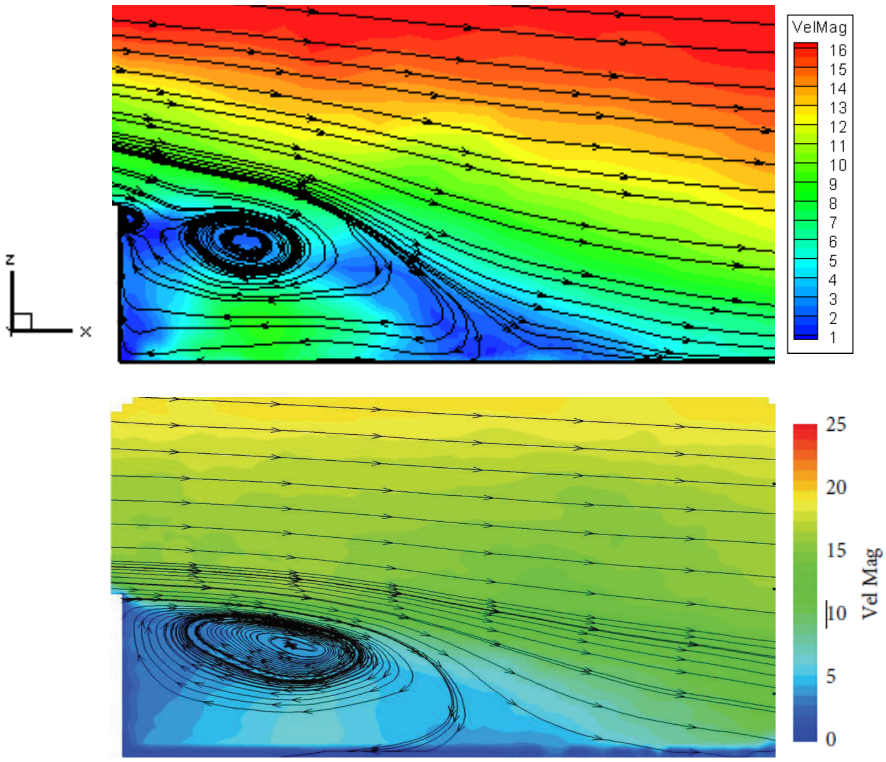


Figure 11: Comparison of streamlines on the vertical slice along centerline with hybrid RANS/LES (top) and experimental data (bottom) for horizontal ship

In this paper, besides the steady state calculations, unsteady RANS/LES simulations are performed to understand the unsteady, random motion of the flow field. Unsteady simulations are initiated from laminar steady-state results, in which 2500 iterations are run. In calculations, the time step is calculated according to CFL number of 0.8 and found as 2.4e-4 second. In every 0.1 second time interval, the instantaneous results are collected. Over simulations of 20 seconds, the results are time averaged in order to obtain mean flow properties. In Figure 12, the time-averaged and in Figure 13 instantaneous unsteady RANS/LES simulation results are given.

Also, the mean velocity distribution over the ship beam at half hangar height and mid-deck are presented with the comparison of instantaneous velocity distribution in Figure 14. As seen from the plot, the velocity fluctuations over the mean values dominate the flow. These fluctuations generate unsteady loading on the rotor blades, which is an unfavorable condition. Also, the spanwise velocity distribution over the flight deck indicates the decrease in the freestream velocity. In such an environment, the thrust produced by the helicopter rotor can be insufficient to compensate the necessary thrust for hovering.

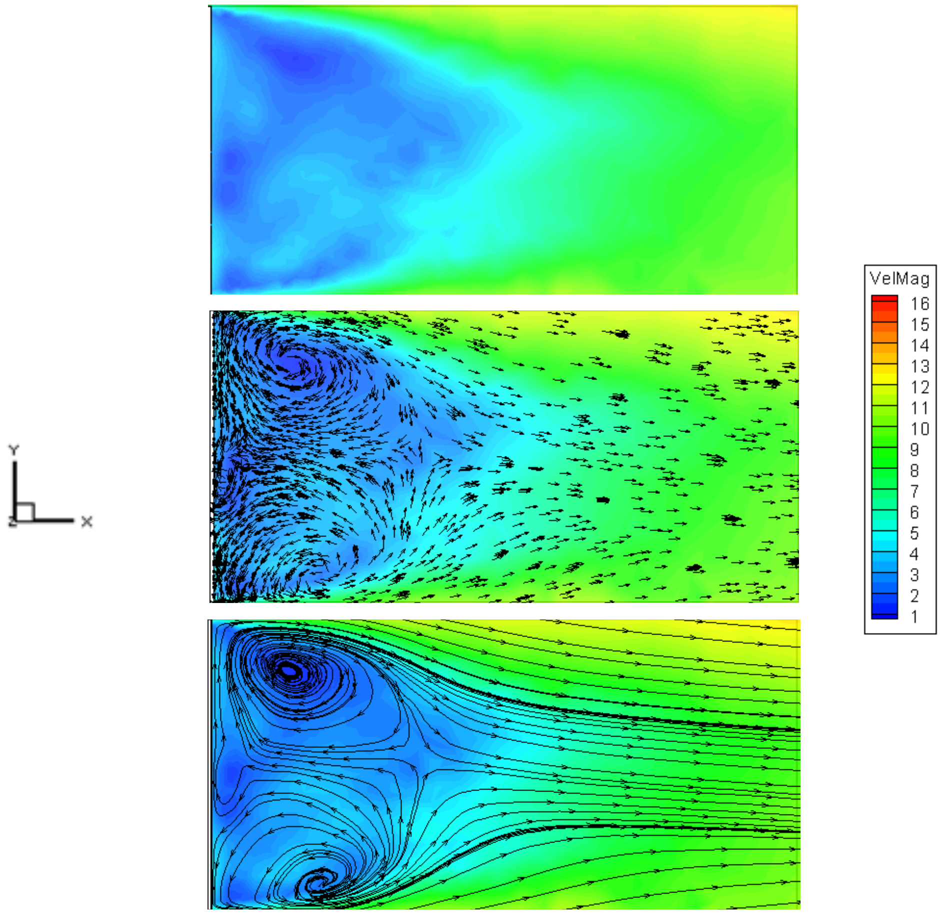
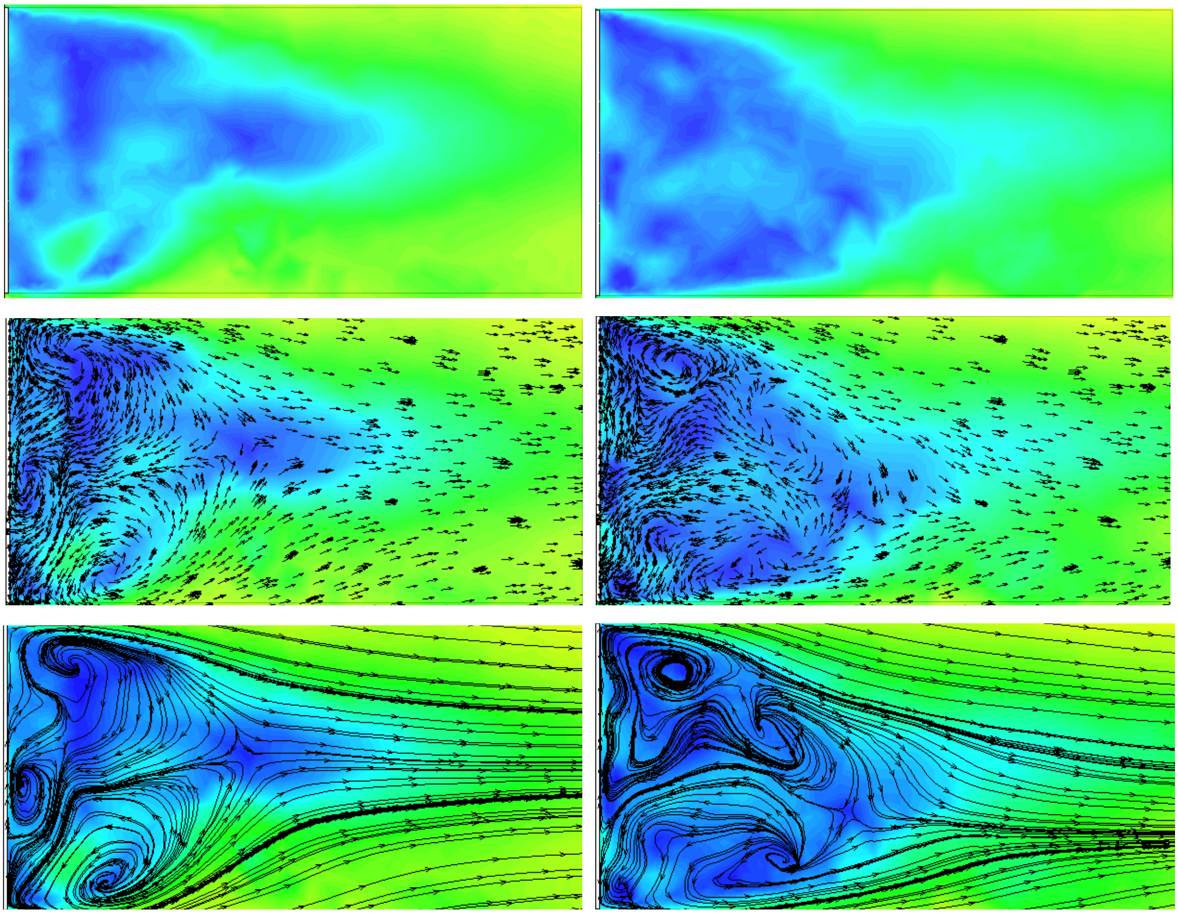


Figure 12: Time-averaged pressure contours, velocity vectors and streamlines on the horizontal slice at half hangar height with hybrid RANS/LES for horizontal ship



(a) t = 15 sec (b) t = 20 sec

Figure 13: Instantaneous pressure contours, velocity vectors and streamlines on the horizontal slice at half hangar height with hybrid RANS/LES for horizontal ship

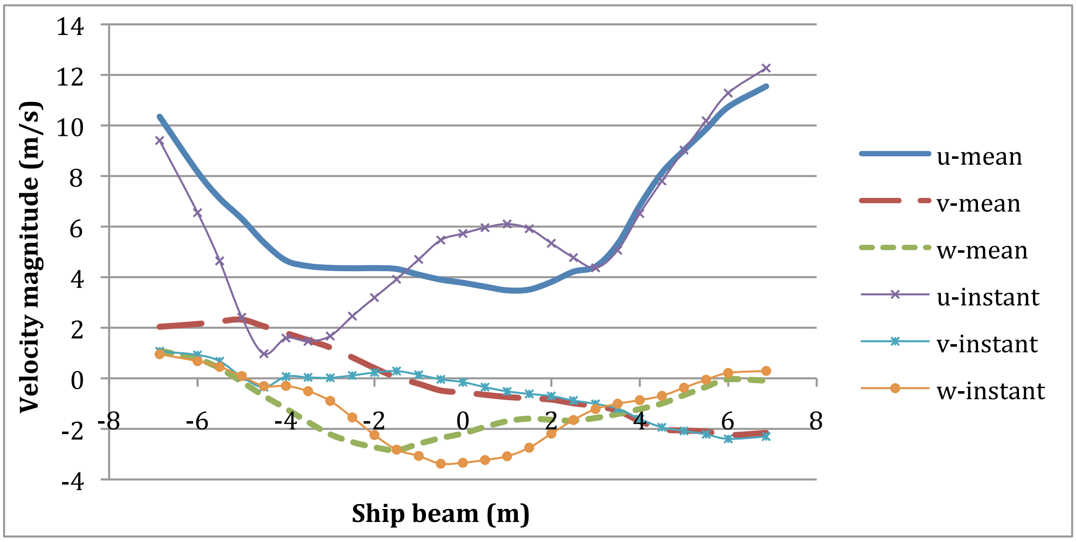


Figure 14: Comparison of time-averaged and instantaneous velocity magnitude across the flight deck for horizontal ship

3.2 Results for Inclined Ship and Comparisons

The effect of the ship motion is approached as an inclined flight deck problem. Therefore, the unsteady simulations are performed for the inclined ship model with the same conditions as previous computational case by using hybrid RANS/LES turbulence model. The computations are conducted for 10 seconds in real time. In Figure 15, the mean flow topology over the inclined flight deck at centerline and z=7.5 m above the waterline is given. It can be said that velocity magnitude decreases due to inclination. This causes rotor to produce lower thrust than it needs to hover over the flight deck. Comparison between the horizontal ship case and inclined case shows that the symmetrical feature of the vortical structures disappears. The instantaneous velocity vector plots for t=5 sec and t=10 sec are also presented in Figure 16. It can be clearly seen that velocity vectors show a little variation with time for a 10 seconds simulations. In Figure 17, the comparison between the inclined ship and horizontal ship is presented in terms of velocity distribution over the ship beam, at 7.5 meter above the sea surface and at the mid of the flight deck.

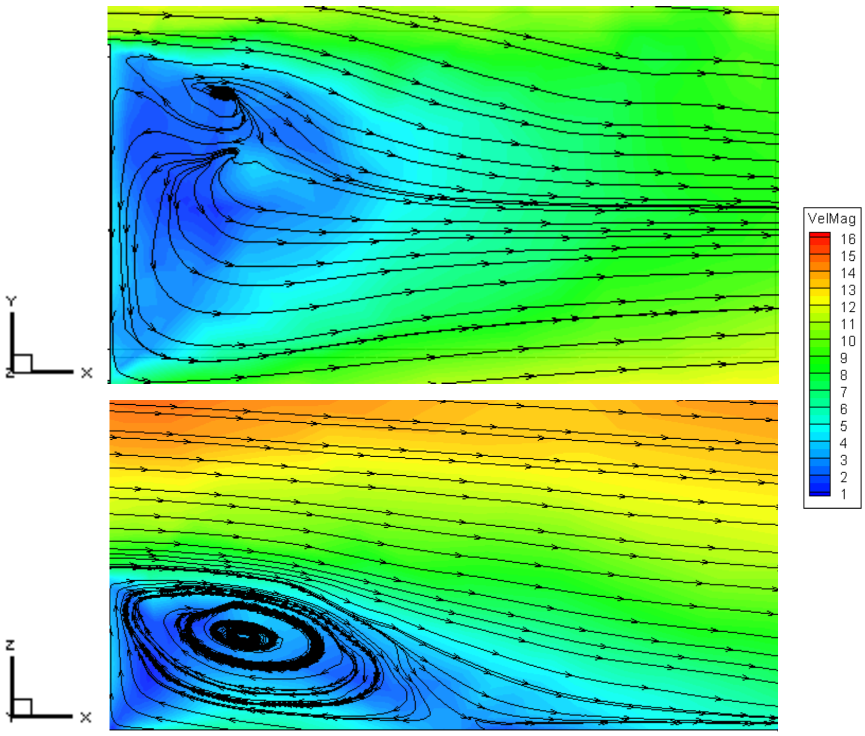
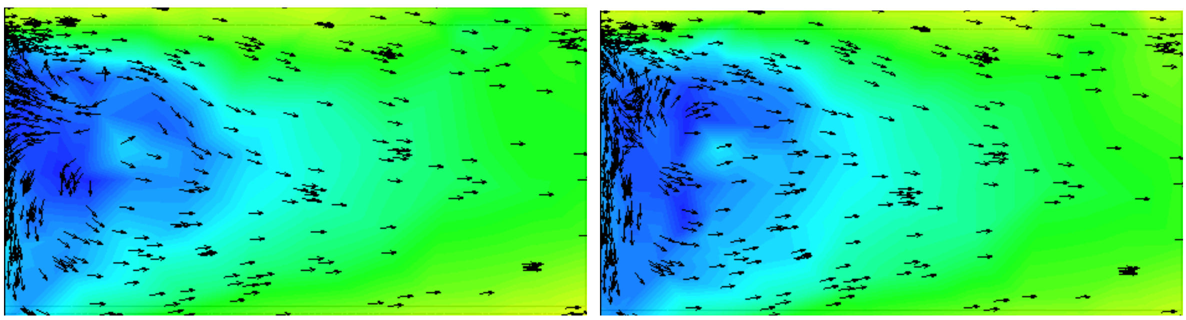


Figure 15: Streamlines on the horizontal slice at z=7.5 m above the waterline (top) and at vertical slice along centerline (bottom) with steady-state RANS for inclined ship



(a) t = 5 sec (b) t = 10 sec

Figure 16: Instantaneous pressure contours, velocity vectors on the horizontal slice at z=7.5 m above the waterline with hybrid RANS/LES for inclined ship

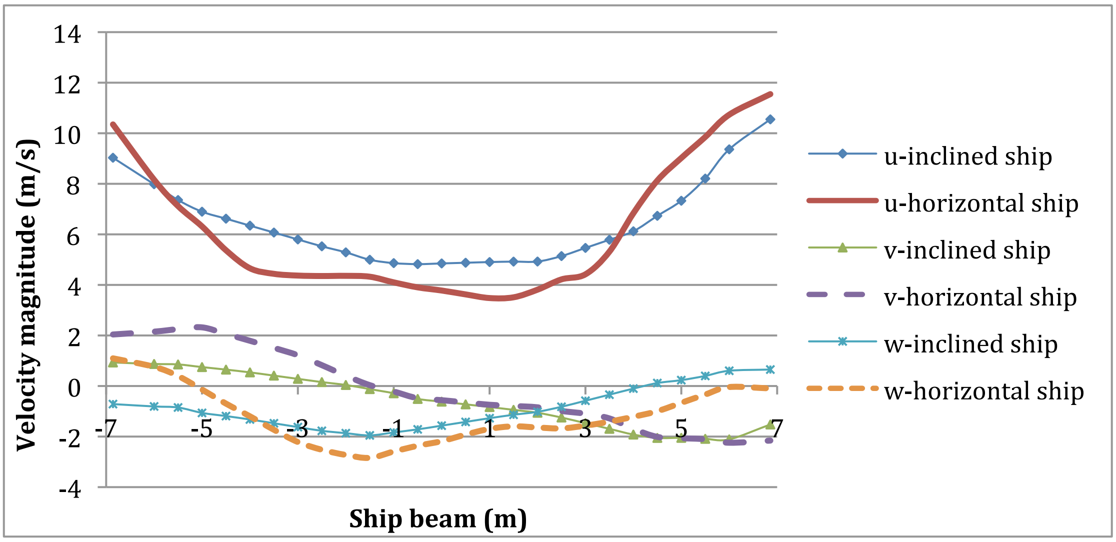


Figure 17: Comparison of time-averaged velocity magnitude across the flight deck for horizontal ship and inclined ship

3.3 Results for Ship with Rotor Model and Comparisons

The ship airwake computations with a rotor disk model are still ongoing. Therefore, unsteady simulation results are limited on 2.5 seconds. The computations are conducted as mentioned in previous simulations. The time step and turbulence model used in computations, and steady-state to unsteady conditions are the same as in the hybrid RANS/LES horizontal ship airwake simulations. In Figure 18, the instantaneous results for horizontal ship are presented for a slice at half hangar height, and the velocity vector plots at centerline are given for t=0.1 sec and t=2.5 sec. It can be seen that velocity magnitude increases with an actuator disk at the hangar height. Also, new vortical structures are observed.

The inclined ship is also modeled with a rotor disk in order to investigate the roll motion of the flight deck with the helicopter rotor. Again, the computational details are the same as the previous case. The Figure 20 shows the flow pattern over the flight deck at 7.5 m above sea level, and the velocity vector plots at y=0 slice. If the case of horizontal ship and rotor combination is compared with this case, the inclined flight deck creates more asymmetric flow. As a result, unsteady nature of ship airwake increases.

4 Conclusion and Future Work

The ship airwake is an important issue for pilots during helicopter shipboard operations. The flow around the superstructure of ship is unsteady, separated, vortical and turbulent. In this paper, the ship airwake is investigated with two different turbulence models for steady-state and unsteady simulations. The results are compared with the experimental data obtained from previous ship airwake studies in the literature. The unsteadiness feature of the ship airwake can be seen from the plots comparing the mean and instantaneous spanwise velocity distributions. Also, ship airwake is affected by helicopter rotor downwash and ship motion due to the sea waves. Therefore, the simulations including a rotor actuator disk model and an inclined flight deck illustrating the roll motion of the ship due to sea waves are performed by using hybrid RANS/LES turbulence model. As a result of ship with actuator disk simulations, numbers of small vortical structures are generated and structure of ship airwake flow gets more complicated. Ongoing computations with rotor disk will be completed to a simulation of 50 seconds to investigate the flow features in more detail. In future, the CFD simulations can be conducted in a coupled way for ship airwake/helicopter interactions by inputting the induced velocities due to ship airwake into the rotor model. In addition, as a future work, the periodic motions will be applied to the ship model to simulate the realistic unsteady ship motion by using overset grid. Also, instead of the actuator disk model, the real rotor blades can be used with overset grids for the ship airwake/rotor interaction simulation.

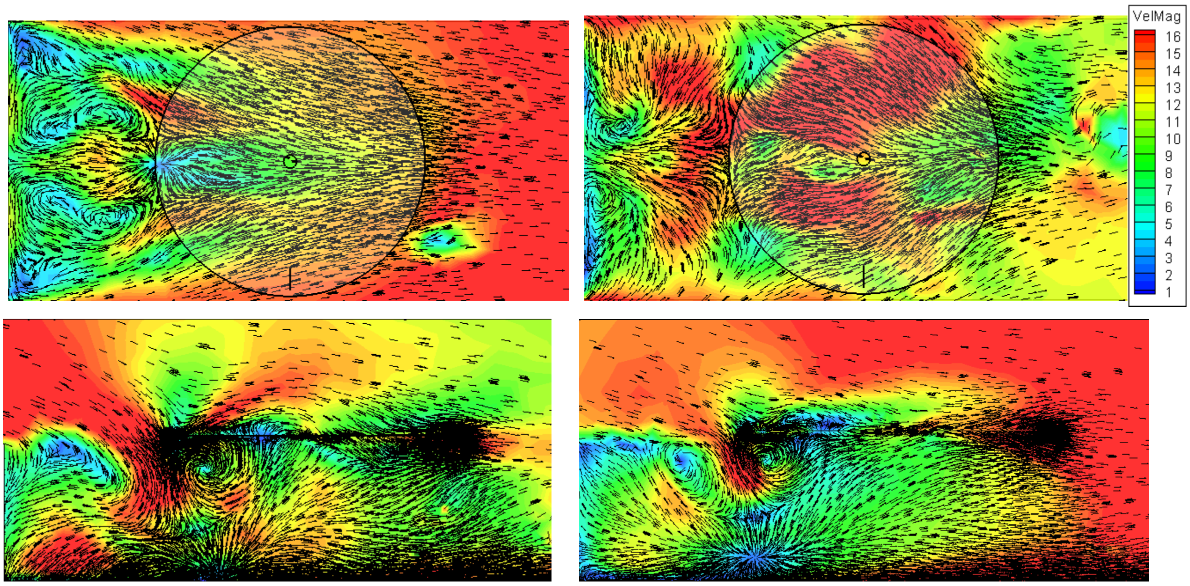


Figure 18: Horizontal ship with rotor - LHS at t = 0.1 sec and RHS at t = 2.5 sec (top views on the top and side views on the bottom) with RANS/LES

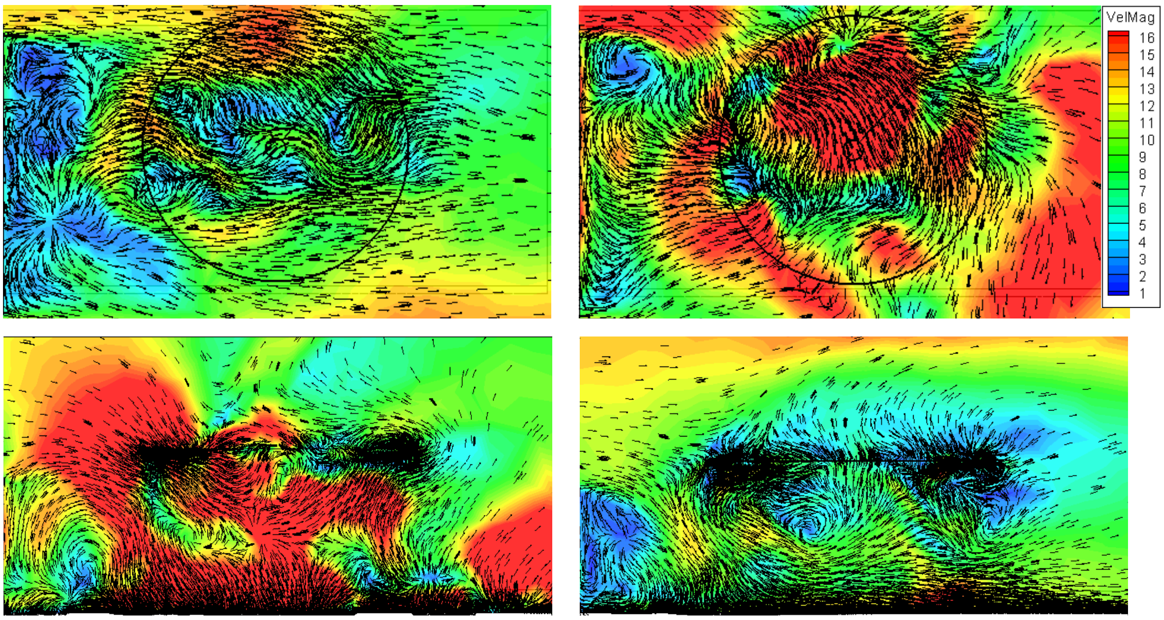


Figure 19: Inclined ship with rotor: LHS at t = 0.1 sec and RHS at t = 2.5 sec (top views on the top and side views on the bottom) with RANS/LES

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