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FLOW STRUCTURES AROUND THE BURJ KHALIFA IN 2D AND 3D

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Summary. As the per capita residential land area decreases, there's a growing demand for skyscrapers, leading to a more in-depth exploration in building aerodynamics research. Consequently, there has been an uptick in the application of Computational Fluid Dynamics (CFD) in the field of architecture. The study of wind loads[1] and the phenomenon of vortex shedding has taken on greater importance due to the reported damage to buildings in numerous literatures. Efforts have been made to calculate the wind speeds at various building heights by utilizing the wind shear power law[2]. This study investigates the vortex shedding phenomenon[3] of wind flow by constructing and simulating the airflow around the Burj Khalifa through a mathematical pipeline, encompassing model acquisition, grid generation, simulation calculation, and post-processing. The research develops two-dimensional cross-sectional models and a three-dimensional model of the tower at three distinct heights. These simulations furnish a wealth of invaluable datasets. Among many computational models, the K-omega SST is selected as the primary model for calculation. The results indicate that while Karman vortex streets manifest in the results of 2D cross section simulations at different heights, the 3D simulation does not produce regular vortex shedding around the Khalifa tower. This implies that Karman vortex streets are not generated in the 3D simulation。

1 INTRODUCTION

As aerodynamics advanced, researchers began to study wind loads on buildings and wind-induced vibrations from an aerodynamics perspective. Particularly, in the wake of the Takoma Bridge incident in the 1940s, observers became acutely aware of the significant impact of wind on buildings[4]. Von Karman (1954) postulated that the bridge damage stemmed from vibrations induced by the Karman Vortex street while some other researchers subsequently debunked this notion, proposing that the collapse was not directly attributable to it. In the 1960s, calculations and experiments showed that the Tacoma Bridge was destroyed by wind, causing Karman Vortex Street when a specific velocity of fluid passed through the side wall. The periodic shedding of the Karman Vortex Street generates alternating side forces perpendicular to the flow direction on the object, forcing the bridge to vibrate[5]. When the shedding frequency synchronizes with the natural frequency of the bridge structure, resonance ensues, resulting in damage [6].

It was not until the 1990s that the cause of wind-induced destruction of Tacoma Bridge was clearly understood. The structural instability is caused by the total damping of the structural mode of the bridge changing from positive to negative when the bridge encountered a certain critical wind speed, a phenomenon known as flutter[7]. While Von Karman's assessment proved incorrect, his Karman Vortex Street theory remains highly esteemed in the architectural field. Engineers employ calculations and wind tunnel model experiments during the design of high-rise buildings to prevent any potential damage caused by vortex shedding[8]. As more skyscrapers are built nowadays for resource efficiency, it presents unique challenges to building aerodynamics[1]. Vortex shedding can induce significant stress levels, necessitating the need of stronger or more materials in construction[2]. It is possible to study this by simulating the case of Burj Khalifa, specifically designed to break the vortex shedding and reduce the stress on the building structure. Therefore, his study is intended to investigate the vortex shedding phenomenon by constructing 2D and 3D fluid structures, simulating wind flow around the Burj Khalifa and developing 2D and 3D models based on K-omega SST model.

2 LITERATURE REVIEW

Vortex shedding refers to the formation of vortices at the rear of an object, which periodically detach from either side, resulting in the formation of a Von Karman vortex street([9]. The fluid flow past the object creates alternating low-pressure vortices on the downstream side of the object[10]. Vortex shedding was one of the causes proposed for the failure of the original Tacoma Narrows Bridge in 1940s. Von Karman reckoned that the failure was caused by vortex-induced resonance triggered by the formation of a vortex street. The bridge vibrates at a natural frequency and eventually leads to the collapse as the wind passing through the bridge section forms the Karman Vortex. Under the action of external excitation load generated by the vortex alternating shedding, the structure responds to vibration and resonance happens precisely because the shedding frequency of vortices matches the natural frequency of the structure. This is described by the equation below:

$$I[\ddot{\alpha} + 2\zeta_\alpha \omega_\alpha \dot{\alpha} + \omega_\alpha \alpha] = A\cos(\omega t) \quad (1)$$

where the left side of the equation represents the displacement, velocity, and acceleration components of the structure's motion, and the right side accounts for the external excitation forces, which is crucial in our analysis.

Atmospheric boundary layer (ABL) usually refers to the lowest layer of the atmosphere, i.e., the area near the earth's surface. When the atmosphere flows over the surface, rough objects on the ground such as grass, sand and trees impede the flow, generating ground friction and resistance [11]. This frictional resistance is transmitted upward due to the turbulence in the atmosphere, and gradually weakens with the increase of height, which can be ignored when reaching a certain height. The ABL typically spans a height range of about 300 to 1000 meters, but this can vary based on meteorological conditions, topography, and ground roughness [12].

The Burj Khalifa is situated in Dubai, near the heart of the Middle East, amid a vast expanse of flat desert landscape overlooking the Persian Gulf. Burj Khalifa is the tallest building globally, with a height of 828 meters and 162 floors. Its subtly asymmetrical design is engineered to break the vortex shedding and thus reduce the adverse effects on the structure. Inspired by the structure of Hymenocallis' petals and stems, designers implemented the organizing principle between the wings and the central core of the Burj Khalifa[13]. The concrete structure of the tower is configured in a Y-shape on the floor plan, with the three wings resembling petals, each of which has its own concrete core and a core surrounding it. The hexagonal central core of the building is evolved from the flower stem. This design allows three wings to be connected to each other, with four groups of structures that are self-supporting and yet mutually supportive, with a rigorous geometry that enhances the Burj Khalifa's torsional resistance and reduces the impact of wind power while maintaining structural simplicity.

Peter Irwin [12] conducted research on the wind engineering for Burj Khalifa, to study the meteorological conditions in the region, particularly within atmospheric boundary condition layer. It shows the researchers conducted a series of iterative wind tunnel tests and designed regressions, feeding the results of the wind tunnel tests back into step of the design. The test results indicate that at higher range of the test speed the results were not affected by Reynolds number. In the design process, the data from several local weather stations were used, including Dubai Airport, Doha, Abu Dhabi, Sharjah and Ra's al Khaimah[12].

3 METHODOLOGY

This study employs Computational Fluid Dynamics (CFD) technology to simulate the airflow structure around the Burj Khalifa, incorporating a 2D model and a 3D model. For the 2D model, the vortex shedding was observed by capturing three cross-sections at different heights of the Burj Khalifa and establishing a velocity profile through the wind shear power law. A structured mesh was used to generate the 2D model mesh. The output results were acquired via Fluent, and Fourier transforms were then applied in Matlab to calculate the dominant frequencies. A 3D model may provide deeper insights into the actual vortex shedding behaviour. Although some studies suggest that a structured mesh surpasses an unstructured one in terms of performance, this study used an unstructured mesh for the 3D model mesh division due to the complexity of the 3D geometry. A grid dependency study was required to ensure that the results from meshes with different numbers of cells, based on the same geometric model, do not affect the outcomes. As the transient state needs a significant amount of simulation time, the mesh dependency study was conducted with steady-state conditions to reduce the time costs of the 3D simulation. For the 3D simulation parameters, most settings remained identical to those in the 2D model, except for the entrance speed, which includes a function to account for speed changes with height. The steady-state simulation in the initial stages of the 3D model performed satisfactorily, but subsequent transient simulations frequently encountered errors. Despite successfully computing steady flow, the residual value remained high and tended towards divergence, indicating that the mesh quality was insufficient for transient simulations, Transient simulations have stringent requirements for grid quality. After refining the grid several times to enhance its quality, we finally achieved successful transient simulation. The method for fine-tuning mesh quality includes adding a density box during mesh generation to control mesh density and performing mesh dependency tests to determine if the mesh's impact on the results meets expectations. The results show that the grid generation for the 3D model is computationally time-consuming, primarily due to the complex structure of the Burj Khalifa.

The 3D model was sliced to get three 2D cross-sections model.

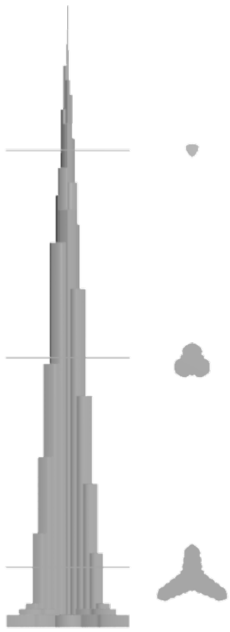

Figure 1. Khalifa model

For 2D models, this study uses three different height cross-sections of Burj Khalifa, i.e., 80m, 355m, and 632m respectively, and calculates wind speed as inlet velocity for three different height and velocity profile based on wind shear power law as shown in Equation 2:

$$u_2 = u_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{2}$$

where the u and h are velocity and height of cross-sections respectively. Furthermore, since the 2D model is more conventional and the structured mesh offers higher quality than unstructured mesh, with better control over the number of nodes and cells, this research opted to generate the 2D mesh using a structured approach. Additionally, the number of nodes in the 2D meshes at the three heights is set to be the same.

At altitudes of 80 m, 355 m, and 632 m, the wind speeds are 31.4 m/s, 38.7 m/s, and 42 m/s respectively, acting as velocity inlets. This study leverages a Courant-Friedrichs-Lewy(CFL)-based calculation method, allowing for automatic updates to the step size accordance with the CFL number. The initial time step size was set to 1e-5, with a total of 10,000 time steps. This choice was informed by prior 2D simulations, where setting the total time steps to 1,000 only resulted in insufficient time for clear visualization of the vortex shedding process.

Standard steps including setting grid size were followed for mesh generation. Once the grid is generated, the mesh quality is validated based on a histogram showing different grades of grid quality. The results show that for the 3D model the overall grid quality declined due to the spire structure at the top of the tower, which is significantly smaller. After setting the grid size, the top area enlarges, which affects the overall quality. At this point, it becomes necessary to adjust the low-quality mesh areas using surface mesh and line mesh techniques. However, this model is fundamental. It was found that after initially attempting to generate the mesh by simply adjusting the parameters, the resulting mesh was only suitable for steady flow simulations, not transient flow simulations.

Subsequently, during the grid generation process, the lines in areas with low grid quality were selected, and the number of nodes was increased. This is because, in the grid, the number of nodes is associated with the number of cells. If the number of nodes is increased, the grid size will decrease, but the grid density will increase. This approach is similar to a structured grid, where the more nodes you have, the denser the grid becomes. The mesh quality is shown in figure 2.

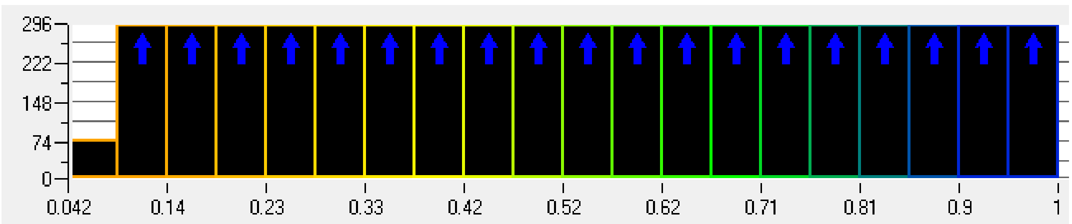

Figure **2**. Mesh quality

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4 RESULTS AND DISCUSSION

In the experiment, the wind shear power law equation as shown equation 2 for wind and height variation were calculated from local wind speeds at different heights. Through two groups of data known, 10m:23.5m/s and 600m:41.7m/s [12], one can receive wind shear index=0.1401, same as general simulation:0.143(1/7). Subsequently, the velocities at different heights of Burj Khalifa can be calculated using wind shear power law equation, as shown in Figure 3.

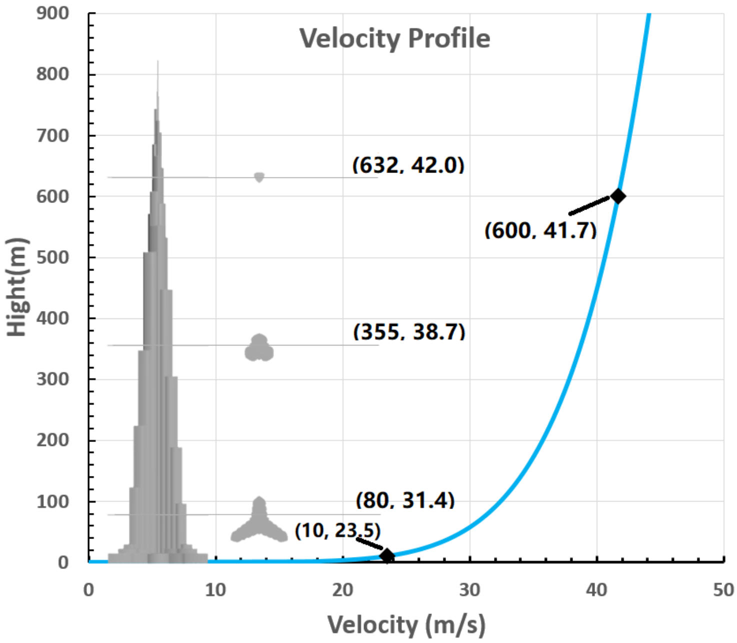

Figure 3. Velocity profile

The simulation was then carried out, and subseqently the Fourier transformation was applied to generate the following plots 4, 5 and 6.

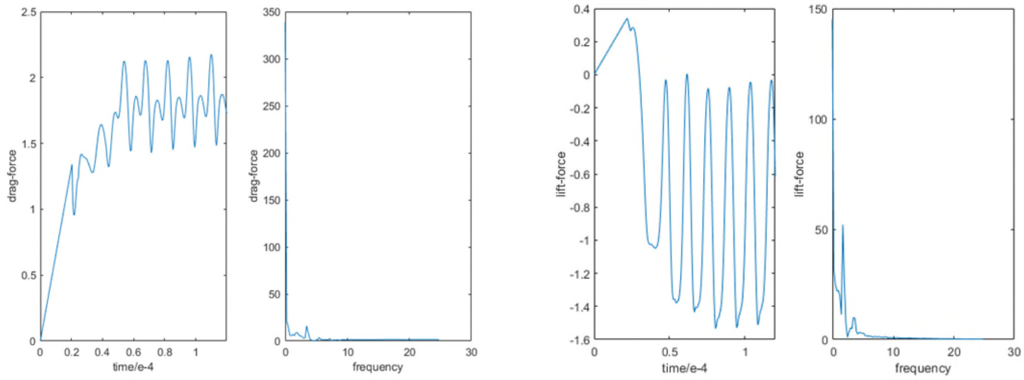

Figure 4. Low height drag and lift.

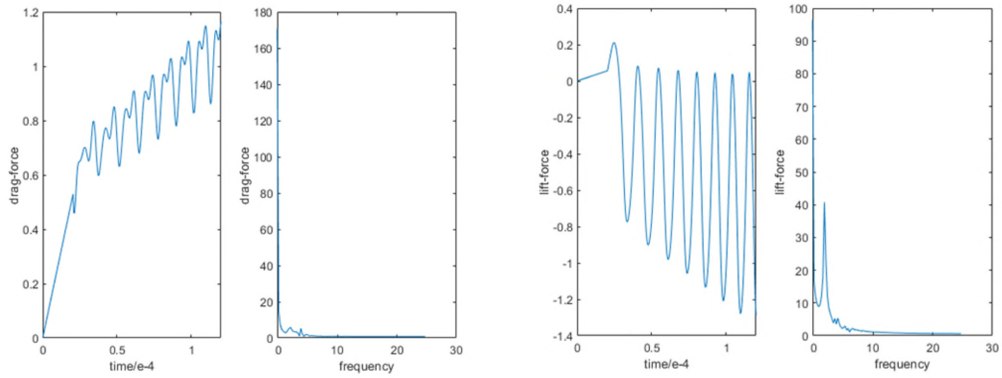

Figure 5. middle height drag and lift.

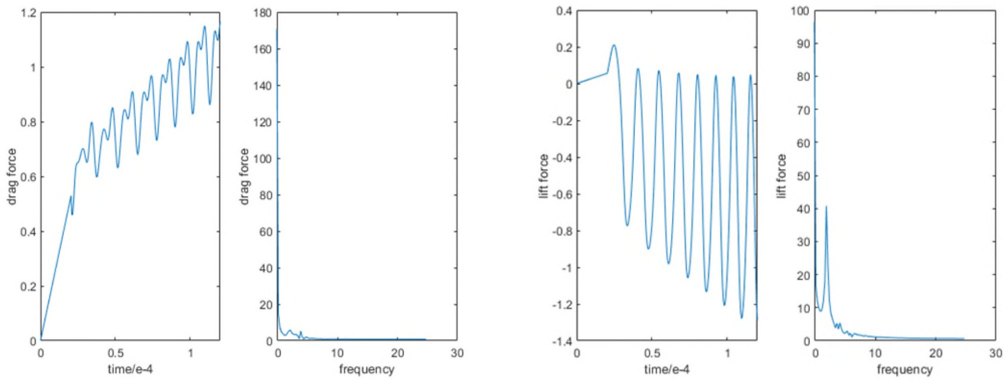

Figure 6. Upper height drag and lift.

From the figures, it is evident that the vortex shedding and the frequencies of vortex shedding are consistent at each height, indicating that the Burj Khalifa has been designed precisely and the results align with expectations. One only needs to examine the vortex street situation at a single height. Figure 7 exhibits the evolution of vortex shedding at various times throughout the simulation process. One can observe the three stages of vortex creation, i.e., generation, interaction on the right side of the structure, and shedding. These findings corroborate the description of the Karman Vortex Street in last section.

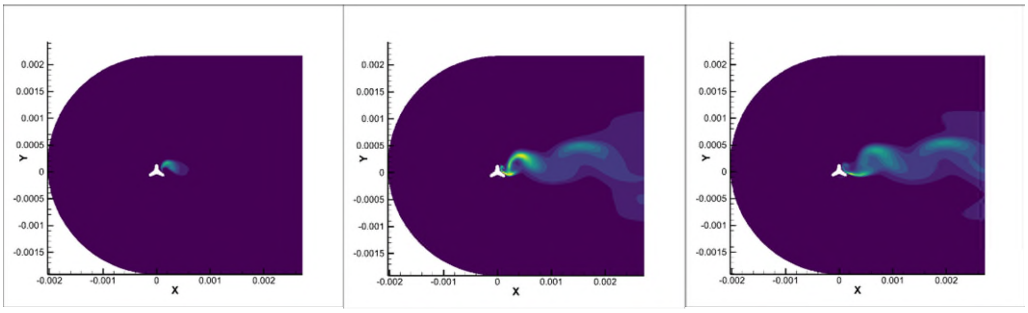

Figure **7**. Vortex shedding developments.

From the previous simulation results and the frequency data, it appears that the frequency of vortex shedding remains essentially consistent across different heights and stabilises after a period of time.

Then, a 3D simulation is performed, and the data is processed in the same manner as in 2D simulations, as shown in Figure 8.

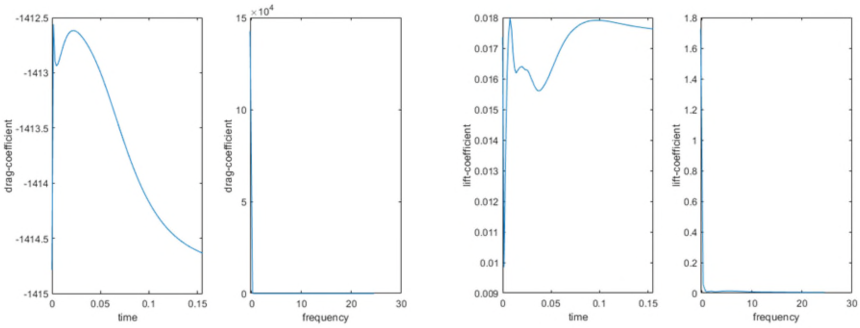

Figure 8. 3D drag and lift coefficient and frequency.

Figure 8 shows no evidence of regular vortex shedding, indicating that the Karman Vortex Street was not formed. This suggests that the results of the 3D simulation differ from those of the 2D simulation, with no clear or dominating vortex identifiable, unlike in the 2D case.

In the 2D simulation, vortex streets are visible in the simulation of three sections at different heights. This indicates that the Burj Khalifa's design has successfully avoided generating Karman Vortex Streets, likely due to the interaction of the flow around the different height of building. The variation in eddies occur mixing, preventing major shedding frequencies from building up. Therefore, from the 3D results, it is evident that although the 2D shape clearly shows vortex streets, the unique shape and variation in the 3D simulation prevent the formation of a stable vortex shedding frequency, thereby avoiding vortex streets generation.

5 CONCLUSION AND FUTURE WORK

As the population grows, the per capita land area decreases, leading to an increasing demand for skyscraper construction. With numerous incidents of wind-related building destruction, research on aerodynamics becomes increasingly crucial as building heights escalate. This study focuses on investigating the fluid dynamics around the tower structure of Burj Khalifa. In this study, the 2D simulation revealed the presence of the vortex shedding problem, resulting in the formation of a Karman vortex street. However, the results of the 3D simulation present a contrast, showing only eddies without regular vortex shedding, and consequently, no formation of a vortex street. The results validate the effectiveness of employing aerodynamics in architectural design through Computational Fluid Dynamics (CFD).

Following the Burj Khalifa's lead, designers can derive inspiration from this iconic building for both design and research purposes. Conducting CFD simulations with scaled-down models with various parameters can enhance cost-efficiency. The Burj Khalifa remains within the atmospheric boundary layer. However, this context may shift as buildings elsewhere surpass its height. Moreover, the results should be validated by extending the simulation duration to observe potential changes in vortex shedding frequency over time, ensuring a fully developed state reached. While the simulation's flow time is 0.1 seconds, Fourier transform calculations for frequency need to reach 1 second. And it's also crucial to consider multiple ABL factors beyond velocity, such as density and viscosity.

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