Hydrodynamic Analysis of Hurricane Passing Through Single-family Houses with Three Different Roof Designs

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ABSTRACT

Over the past decade, hurricanes caused by climate change have become more frequent. The aerodynamic performance of the house becomes increasingly important. This paper attempts to have a hydrodynamic analysis of the flow field form of wind around some single-family houses that are in different roof shapes by Computational Fluid Dynamics (CFD), which is based on the computer program ANSYS Fluent 2022 R1. Therefore, it can be simulated that the wind with a high velocity blows some single-family houses that have different roof shapes to show the information about hydromechanical properties, and provide ideas for designing houses in hurricane-prone areas. The results show that hip-roof house is relatively less affected by hurricanes, and concentrated construction of compact residential areas can reduce the impact of hurricanes.

Keywords: Computational Fluid Dynamics, roof shapes, flow field form, hurricane, hydromechanics

1. INTRODUCTION

Tropical cyclones are expected to increase in intensity as the planet continues to warm over the next decades [2]. With the increasing intensity and frequency of hurricane activity, it becomes more important to figure out the aerodynamic performance of the housings, which can explore some sustainable and inexpensive design of houses. In 2013, Hurricane Sandy caused a devastating disaster in many countries, which included Cuba, the Dominican Republic, Jamaica, the Bahamas, the United States and other countries, causing billions of dollars in economic damage and heavy human casualties [3]. Yue Li and Ellingwood showed that Most hurricane-damaged homes could be avoided with structural improvements [4].

In this paper, it is simulated that three single-family houses with different common designs of roofs are hit by a hurricane, whose speed is 33 m / s. In this process, CFD is used to calculate the distribution of hurricane pressure, kinetic energy, velocity and other physical quantities around the single-family house when the hurricane passes by it. By comparing the results of the three roof designs, possible structural and design improvements are obtained.

In fact, there's been a lot of research on making houses more resistant to hurricane damage which had good results. Eri Gavanski published an article in 2013 about wind loads on the roofs of typical low-rise timber houses, which showed that roof shape and countercurrent topography have the greatest influence on wind loads acting on roofs [5]. In this paper, flat-roofed houses, hip-roof houses and gable-roof houses with different angular ratios were chosen to simulate the pressure distribution on the roof when it was blown by the wind. Aly Mousaad and Nader published an article in 2021 which was to understand the performance of parapets in reducing local and area average roof pressure [6]. It was pointed out that the installation of the parapet would act as an aerodynamic relief device to reduce lifting loads, and large-scale experiments showed that the higher the parapet was, the greater the reduction of mean pressure.

These studies have focused on the impact on the houses themselves. However, this paper will describe the wind field formed when the hurricane passes the house by CFD, so as to provide new ideas to reduce the impact of the hurricane on the house. This will give engineers more of a theoretical basis to solve problems in the future.

2. MODELS AND THEORY

2.1 house model

Three single-family houses with different roof designs were selected for this study, whose width, length and height are all about 9m, 10m and 8m. As for the gable-roof houses and the hip-roof houses, they all have roofs at 30 degrees. The hurricane will blow into each of them from a horizontal direction.

2.2 Simulation

This study performs the simulation on ANSYS Fluent 2022 R1, which is a computer program for numerical simulation of fluid dynamics. It is well suited for analyzing flows around two-dimensional and three-dimensional geometry. Moreover, it also has outstanding applications in multiphase flows, fluids around rigid and movable walls, propagation in open channels, aerodynamics, energy, magnetic field phenomena, thermodynamics, and similar fields. In the process of simulation, SOLIDWORKS 2021, Design-Modeler program, ANSYS Meshing and CFDpost also provide more convenient access.

There are three steps to creating a mathematical model in ANSYS Fluent 2022 R1. The first step is preprocessing. In this study, the modeling of three single-family houses with different roof designs was carried out in SOLIDWORKS 2021. The model is then imported into the Design-Modeler program to create a fluid domain that is 30 meters in the X direction and 15 meters in the Y and Z directions. After creating the single-family house model and fluid domain, it is necessary to create grids. ANSYS Meshing provides tetrahedral mesh, hexahedral mesh, sweep mesh and other mesh creation methods, of which tetrahedral mesh is employed for meshing.

The next step is to perform simulation calculations, including defining the properties of the numerical model, such as types of turbulence modes, initial and boundary conditions, iterative algorithms, mathematical equations, and material properties. A standard k-ε turbulence model with two characteristic equations is utilized in the viscosity model. The notation k is the kinetic energy in the fluid and the notation ε is the dissipation of this flow kinetic energy. The standard wall function is adopted to solve it [7]:

$$\frac{dk}{dt} = \frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\frac{v_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + P - \varepsilon \qquad (1)$$

Where ε is the dissipation rate, v_t is the turbulent viscosity and P is the energy production rate. The second part of this equation is:

$$\frac{d\varepsilon}{dt} = \frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\frac{v_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right) + C_{\varepsilon_1}\frac{p_\varepsilon}{k} - C_{\varepsilon_2}\frac{\varepsilon^2}{k} \quad (2)$$

Where $C_{\varepsilon_1}\frac{p_\varepsilon}{k}$ is the production rate and $C_{\varepsilon_2}\frac{\varepsilon^2}{k}$ is the dissipation rate. The transient model is used in this simulation. The entry type is defined as a velocity inlet with a speed of 33m/s and outlet type is defined as pressure outlet with gauge pressure of 0 Pa. As for time advancement, the number of time steps is 100 and the time step size is 0.1s. The max iterations are 100 which is to an acceptable level.

The final step is postprocessing, which involves representing the collected data in vector and cloud images. In this way, the distribution and characteristics of relevant physical quantities in the space near single-family houses can be more intuitively displayed. CFDpost provides the vector, contour, streamline and volume rendering. In addition, CFDpost can also show the dynamic changes of various physical quantities in the process of hurricane blowing in the form of animation, which is a function of CFDpost.

3. RESULTS AND DISCUSSION

The k-ε turbulence model and the standard method were adopted to establish the single-family house model, and the distribution of hurricane velocity and pressure around the single-family house were analyzed under the wind speed of 33m/s. At the same time, based on the data collected, possible options for reducing hurricane damage to single-family homes are proposed.
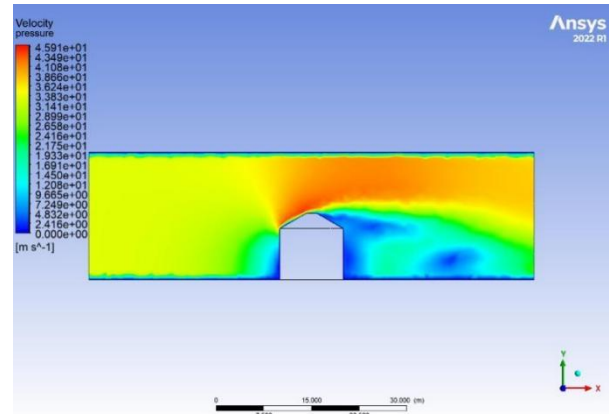

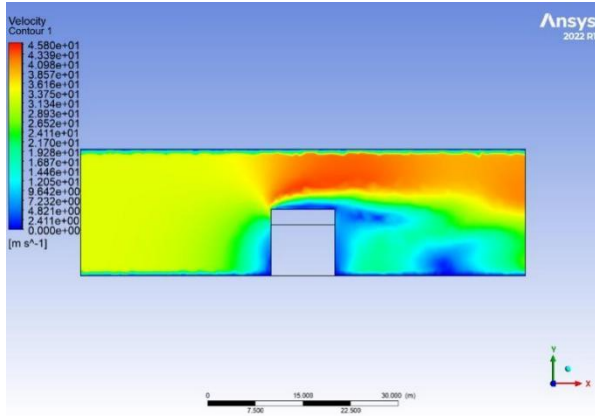**Figure 1**: the velocity distribution of hip-roofed house

Figure 2: the velocity distribution of gable-roofed house
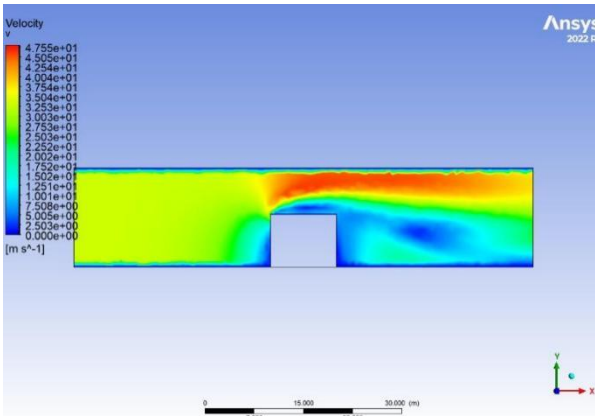

Figure 3: the velocity distribution of flat-roofed house

These three images show the distribution of hurricane velocities around three types of single-family houses when the Z-axis value is 0 in the XY plane. By comparing the three pictures, it can be concluded that for the houses with hip roofs and gable roof, the velocity distribution of the hurricane on their central axis plane is similar, and the wind speed at the rear of the house is different after the hurricane blows through the house. In contrast, the speed distribution of the hurricane before passing the flat-roofed house was not significantly different from that of the other two types of houses. The speed of the hurricane increased at the eaves when it came into contact with the house. whereas a hurricane moves more slowly below the height of a flat-roofed house.

It can be seen that after passing through the central axis plane of these three houses, the wind speed decreases significantly within the range of the height of the house, and the wind speed decreases most obviously after passing through the flat-roofed house. This may provide a design solution for hurricane resistant single-family houses. That is, single-family houses can be built close to each other with a distance of about 10m or less. In this way, the front house can effectively create a zone of low wind speed behind itself, thus minimizing the impact on the whole residential area. In the same way, parapets or trees of a certain size could be built around residential

areas, and also create areas with low wind speeds behind them to protect residential areas from hurricanes.
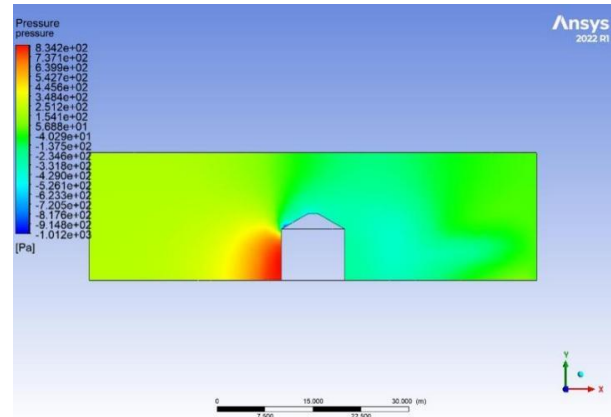

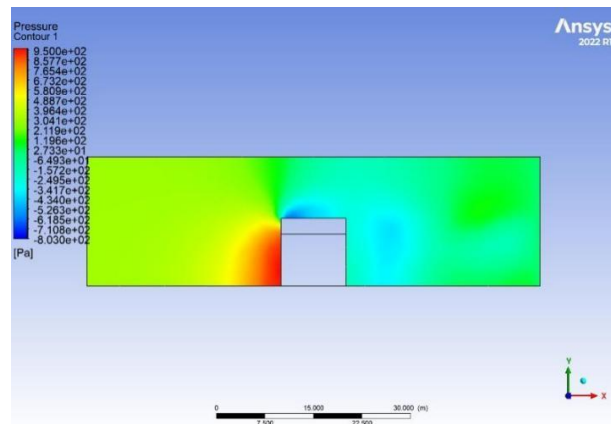**Figure 4**: the pressure distribution of hip-roofed house

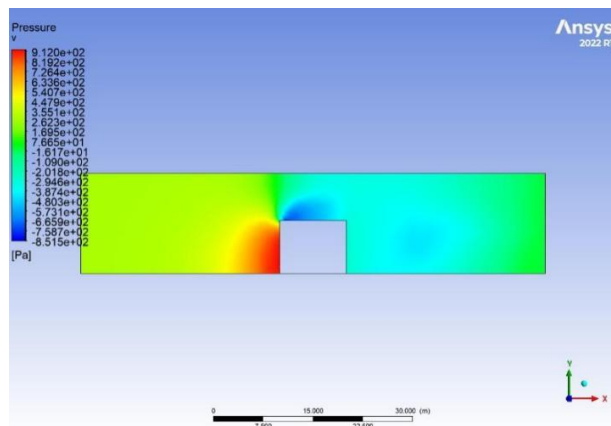**Figure 5**: the pressure distribution of gable-roofed house

Figure 6: the pressure distribution of flat-roofed house

These three images show the distribution of hurricane pressure around three types of single-family houses when the Z-axis value is 0 in the XY plane. By comparing these three pictures, it can be found that the wind pressure is the largest in the front contact part of the house below the height of the eaves. However, in these three images, the distribution of hurricane pressure on the roof and behind the house is different. For gable-roof houses and flat-roof houses, there is a large negative pressure on the roof, and

there is an obvious negative pressure area at the rear of the house. For a hip-roof house, the pressure distribution in the roof part is much better, and the overall pressure is significantly smaller. Meanwhile, the negative pressure behind the house is relatively small.

After comparative analysis, it can be seen that a hip-roof house can reduce the pressure of hurricane around itself. The hip-roof can be considered more when designing the roof shape of a single-family house. However, it is also easy to see from the picture that the front wall and eaves of the house have a large wind pressure distribution. This means paying special attention to the performance of these parts when designing the house. Compared to the speed map of a hurricane, a properly sized windbreak or parapet in front of a house can actually put relatively little pressure on the house.

4. CONCLUSION

The topic of this paper is to use Computational Fluid Dynamics (CFD) to simulate the distribution of physical quantities such as velocity and pressure around three single-family houses with different roof designs when a hurricane passes by them. Tetrahedral mesh is used in grid division. The standard K - ε turbulence model was used in the calculation. The simulation results show that the wind speed behind the house decreases obviously after the hurricane blows through the house. Flat-roofed houses have the least wind speed in the rear area of the house. As for the pressure distribution of a hurricane, a hurricane has a lot of wind pressure on the front and eaves of the house. Hip-roof house designs can reduce the impact of hurricane pressure on the house. Therefore, hip-roof houses can be used more often in hurricane-prone areas. In addition, when planning residential areas, keep houses as close as possible to reduce the impact of hurricanes. Moreover, the simulation also shows that windbreaks or parapets planted around residential areas can reduce the impact of hurricanes and provide housing protection.

There are many areas for further studies. This simulation does not account for the stress distribution on a house during a hurricane. The angle of a hip-roof house and a gable-roof house also affects its stress from hurricanes [8]. Further research could focus on the impact of the location of multiple single-family houses on the ability of the entire residential area to withstand hurricane damage. It is believed that future research will eventually allow people to minimize the loss of life and property caused by hurricane disasters.

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