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Enhancement of CFD validation exercise along the roof profile of a low-rise building

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Abstract. The aim of this study is to enhance the validation of CFD exercise along the roof profile of a low-rise building. An isolated gabled-roof house having 26.6° roof pitch was simulated to obtain the pressure coefficient around the house. Validation of CFD analysis with experimental data requires many input parameters. This study performed CFD simulation based on the data from a previous study. Where the input parameters were not clearly stated, new input parameters were established from the open literatures. The numerical simulations were performed in FLUENT 14.0 by applying the Computational Fluid Dynamics (CFD) approach based on steady RANS equation together with RNG k-ε model. Hence, the result from CFD was analysed by using quantitative test (statistical analysis) and compared with CFD results from the previous study. The statistical analysis results from ANOVA test and error measure showed that the CFD results from the current study produced good agreement and exhibited the closest error compared to the previous study. All the input data used in this study can be extended to other types of CFD simulation involving wind flow over an isolated single storey house.

1. Introduction

In wind engineering, Computational Wind Engineering (CWE) is one of the methods to solve wind engineering problems. This method has been widely used due to the advancement in the technology and computerization as stated by [1] and [2]. CWE is defined as the use of Computational Fluid Dynamics (CFD) analysis for wind engineering applications. CFD simulations provide abundant flow information that can be visualized at any instant time and most importantly, solve wind-related problems at a reduced cost compared to wind tunnel experiments [3].

There are several CFD applications to building analysis related to airflow assessment, wind condition around buildings, ventilation of buildings and wind driven rain on building façade [2]. Besides that, CFD is also used to predict the effects of wind on building and on the people in and around them [4], to predict wind flows around buildings and structures under conditions very close to the actual state [5] and to evaluate the interaction between wind and structures numerically [6]. However, the validation exercise between CFD and experimental data can be in be very complex and tedious. Generally, there are many parameters need to be carefully considered especially those
associated to the atmospheric boundary layer conditions. This paper demonstrates the enhancement of a validation exercise using published wind tunnel data.

2. Methodology
This section explains the methods that have been applied for the numerical simulation on an isolated gable roof using ANSYS Fluent 14.0. The CFD model was developed based on [7].

2.1. Numerical simulation on an isolated gable roof
The current CFD results were evaluated with the experimental data from wind tunnel test (WTT) and CFD results both from [7]. The simulation was conducted according to the scale of the wind tunnel model (1:30) and the roof pitch was set to be 26.6° as shown in figure 1. In this simulation, $H_e$ is taken as the height of the building.

\[ V(z_{ref}) = V(z) \left( \frac{z}{z_{ref}} \right)^{\alpha} \]  
\[ k = \frac{u_*^2}{\sqrt{\epsilon \mu}} \]  
\[ \epsilon = \frac{u_*^2}{K(z + z_0)} \]

Parameters that were not stated in [7] were assumed or generated using data from other literatures [1][6][8]. Simple parameters such as air density and air temperature were assumed to be 1.225 kg/m$^3$ and 15°C, respectively. It was noted that [9] also used the same values in their CFD analysis. The equation for wind profile followed the recommendations from [10] as shown in equation (1). Similarly, the equations for the turbulent kinetic energy (TKE) and turbulent dissipation rate (TDR) followed the recommendations from [11] as shown in equation (2) and (3). In order to generate the wind flow at the inlet, the User Define Function (UDF) was used and generated in C programming language.

In this simulation, $z$ is the height, $z_{ref}$ is the reference height (0.2 m), $V(z)$ is the wind velocity at reference height, is wind velocity at height $z$ and $\alpha$ is the power law exponent. Meanwhile, $k$ is the turbulent kinetic energy, $u_*$ is the friction velocity while $C_\mu$ is a constant with value 0.09. Following that, $\epsilon$ is the turbulent dissipation rate (varies with height), is Von Karman constant with a value 0.41 and $z_0$ is roughness length.
Figure 2 shows the computational domain size of the current study. It is worth mentioning that [7] only provided the general dimension of the computational domain. The detail breakdown of the lateral, vertical, upstream and downstream of the computational domain was determined based on [5][8][12][13].

![Computational domain size and boundary conditions of the current study](image)

**Figure 2.** Computational domain size and boundary conditions of the current study

2.2. Quantitative test (statistical analysis)

This analysis was conducted on both CFD results obtained from the current study and [7]. In this case, the quantitative tests involved only the values of the pressure coefficients. Two tests were established to determine the similarity of both studies namely homogeneity test and ANOVA test. The homogeneity and ANOVA tests were conducted using SPSS software to test whether the mean $C_p$ from [7] and the current study shows strong similarity or not. Besides that, error measure test was also conducted to determine the lowest error for each case namely the mean absolute error (MAE), normalized absolute error (NAE) and root mean square error (RSME). A number of 24 datasets were tested for each study. These values correspond to the pressure coefficient along the wall and roof at the middle part of the house.

2.2.1. ANOVA test. Analysis of Variance (ANOVA) is a statistical method to test the differences between two or more means. In this study, the test was used to compare the means of several pressure coefficients. It is a way to determine whether the results of $C_p$ are significant or not. This study applied the one-way ANOVA because it has one independent variable (with two levels). The assumption of homogeneity of variance is based on Levene’s test with $\alpha = 0.05$ (95% confidence level). If $p$-value is more than $\alpha$, then the null hypothesis is retained. Post hoc multiple comparisons are the tests of the significant differences between the group means calculated after conducting one-way ANOVA. In this study, Games-Howell test was used when the assumption of homogeneity of variance is not met (unequal variance assume) [14].
2.2.2. Errors measures. Several error measure tests were conducted to describe the goodness and imputation covering the mean absolute error (MAE), normalised absolute error (NAE) and root mean square error (RMSE).

2.2.2(a) Mean absolute error. The MAE is used to measure the difference between the observed and predicted values [15][16][17] and the equation to calculate MAE shown below:-

\[ MAE = \frac{1}{n} \sum_{i=1}^{n} |P_i - O_i| \]  

(4)

2.2.2(b) Normalized absolute error. The NAE is to measure the average differences between predicted and observed values in all cases divided by observed values of pressure coefficient [16] using normalization approach. The equation to calculate NAE is expressed in equation (5).

\[ NAE = \frac{\sum_{i=1}^{n} |P_i - O_i|}{\sum_{i=1}^{n} O_i} \]  

(5)

2.2.2(c) Root means square error. The RMSE is used to measure the success of numerical predictions and summarizes the difference between the observed and expected results of \(C_p\) to provide the average error of model [15]. It can provide error values with the same dimensionality as actual and predicted values. The equation of RSME [15][18][19] is defined as follow:-

\[ RMSE = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (P_i - O_i)^2} \]  

(6)

Where \(n\) is the total number of sample, \(P_i\) is the predicted pressure coefficient and \(O_i\) is the observed pressure coefficient.

2.3. Results and discussion

Wind flow around an isolated gable-roof building was validated using quantitative analysis. Statistical analysis was used to support the result for the quantitative analysis. Further discussion is described in the following subsection.

2.3.1 Pressure coefficient (\(C_p\)) from previous study. Figure 3 shows the pressure coefficients along the roof profile from the current CFD analysis, the CFD results from [7] and Wind Tunnel Test (WTT) results also from [7]. The wall and roof profile were divided according to the respective zone namely Zone A (windward wall), Zone B (upwind slope), Zone C (downwind slope) and Zone D (leeward wall).
The graphs show that the distribution pattern of $C_p$ from the current study matches the distribution pattern of CFD Tominaga and WTT Tominaga for all zones. It can be seen that the windward wall (Zone A) experienced high pressure coefficient as it approached the leading roof of Zone B. Following that there was a sudden drop changing the $C_p$ values to become negative (suction). The $C_p$ increased to be slightly positive (current study and WTT Tominaga) and started to move into suction as it approached the apex of the roof. The suction then continued in Zone C and Zone D. By setting WTT Tominaga as the reference, it can also be seen that the results from the current study were compatible to WTT Tominaga compared to CFD Tominaga and this is particularly true in Zone B, Zone C and Zone D. However, in Zone A, CFD Tominaga showed good agreement with WTT Tominaga compared to the current study.

2.3.2 ANOVA test. The Games-Howell method was conducted on a one-way ANOVA to test the difference between all unique pairwise comparisons. Table 1 shows the results of the multiple comparison. It can be seen that that there was statistically insignificant difference to complete the problem between the group of the current study and the WTT Tominaga ($p = 0.891$), the current study (CFD) and CFD Tominaga ($p = 0.987$) as well as WTT Tominaga and CFD Tominaga ($p = 0.837$). The results also showed that there were statistically insignificant differences between the groups as a whole as since the mean significant different, $p$ is more than 0.05. In other words, the mean difference for all groups was quite close to each other.

| (I) Group     | (J) Group     | Mean difference (I-J) | Significant |
|---------------|---------------|-----------------------|-------------|
| Games-Howell  | Current study | WTT Tominaga          | -0.0938     | 0.891       |
| (CFD)         |               | CFD Tominaga          | -0.0246     | 0.987       |

Figure 3. Distribution of pressure coefficient ($C_p$) for all zones
2.3.3 Error measures. This analysis was performed to determine the accuracy measure and error measure between the current study (CFD) and WTT Tominaga, current study (CFD) and CFD Tominaga as well as WTT Tominaga and CFD Tominaga. Three tests were conducted namely the mean absolute error (MAE), normalized absolute error (NAE) and root mean square error (RMSE) as shown in table 2.

|                  | WTT Tominaga  | CFD Tominaga |
|------------------|---------------|--------------|
|                  | Current study | Current study |
| (CFD)            | 0.0692        | 0.0938       |
| CFD Tominaga     | 0.0938        | 0.891        |
|                  | -0.0246       | -0.0938      |
| WTT Tominaga     | 0.891         | 0.837        |

The results showed that the errors between WTT Tominaga and the current study (CFD) provided the smallest error for MAE and RMSE compared to two other groups while WTT Tominaga and CFD Tominaga contributed the smallest error for NAE measure. Therefore, the overall results indicated that the current study (CFD) result was very close to the experimental result by [7].

3. Conclusion
The used of input data from [7] and other researchers showed enhancement in the validation exercise. The statistical analysis results from homogeneity test, ANOVA test and error measure test showed that the CFD results from the current study produced good agreement and exhibited the closest error compared to CFD Tominaga. All input data used in this study can be extended to other types of CFD simulation involving wind flow over an isolated single storey house. These input data were found to be suitable for flat terrain condition considering parabolic wind profile [6][7][12].

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