Computational wind analysis of an open air-inflated membrane structure

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ABSTRACT

The current research aimed to obtain mean pressure distribution over an air-inflated membrane structure using Computational Wind Engineering tools. The steady-state analysis applied the Reynolds-Averaged Navier-Stokes equations with the $k-\varepsilon$ standard turbulence model. The pressure coefficients were compared with former experimental results to validate the numerical solution. Significant errors were detected close to the critical flow separation points when comparing the numerical results with the wind tunnel tests. However, these errors are local, and the numerical methodology provides accurate results in those areas with minor turbulence motion influence. In general, the numerical solution provided good approximation of the pressure coefficient fields.

KEYWORDS
tensile membrane structure, air-inflated structure, wind action, computational wind engineering, pressure coefficient

1. INTRODUCTION

Membrane structures offer lightweight, environmentally friendly, and cost-effective construction solutions to cover large public spaces like concert halls or stadiums [1]. Moreover, lightweight houses can be built like the ones described by [2], representing cheap shelters for emergency situations. Membrane structures can be permanent or temporary buildings; some even possess the deployable characteristic that allows the change of their configuration whenever needed e.g., deployable umbrellas [3].

Tensile membrane structures are composed of flexible textile membrane and a tensioning system that might include arches, masts, rings, and cables [4].

Pneumatic membrane structures are supported and stabilized by the enclosed, compressed air; therefore, they are extremely light structures. Pneumatic structures can be divided into subgroups: air-supported and air-inflated [4–6]. In the case of air-supported structures, the covered air volume is closed and compressed; therefore, special entrances are built to enter or exit the construction. Air-inflated structures are tensioned by the enclosed, pressurized air in their walls; the structure and the covered space can be open, and no special entrances are needed.

The design procedure of membrane structures must consider the strong relationship between geometry and membrane forces. Special numerical methods are applied to determine the equilibrium shape according to the material properties, tensioning system, and external load actions. With their geometry and prestress, the membrane structures must carry downward and upward wind actions or any snow/rain load without wrinkling, ponding, or fluttering problem [1].

The structural design for wind requires knowledge about the pressure distribution on the structure, which can be given by the dimensionless pressure coefficient ($C_p$). Because of the complex and unusual shapes, those parameters are not given in the Standards for membrane
structures. The pressure coefficients can be obtained by experimental studies or numerical simulations. The Wind Tunnel test (WT) is the most reliable technique related to the wind engineering of structures; however, it is time-consuming and costly. Usually, this technique implies measurements on scaled, rigid models wherein material properties and deformations cannot be considered. Wind tunnel investigations of different membrane roofs are presented in [7–10].

Numerical approaches, also known as Computational Wind Engineering (CWE), apply the governing equations that describe the fluid eddy motions to solve the aerodynamic wind effects around the building [11–13]. This technique may include steady-state or time-dependent analysis where material properties and deformations can also be analyzed (fluid-structure interaction). It should be mentioned that CWE cannot be considered a completely reliable technique, so its validation with experimental results is strongly recommended. Numerical investigations to analyze the aerodynamic behavior of different tensile membrane structures are described in [13–15]. The current research validated the CWE analysis of an open air-inflated membrane.

2. METHODOLOGY

2.1. Former wind tunnel tests

The structure selected for the CWE analysis was previously tested in a wind tunnel [16]. The prototype structure consists of six inflated tubes with a diameter of 3 m (Fig. 1); its total length (L) and height (H) are 13 m; meanwhile, the width (W) is 26 m. The experiments were completed in the open-circuit wind tunnel with a test section of \( 1 \times 1 \times 1.5 \) m of the Autonomous University of Yucatan, Mexico. The 3D printed model had a scale ratio of 1:72.5. The pressure on the external and internal surface of the model was measured at 102 points for three wind directions 0°, 45°, and 90°.

2.2. Numerical analysis

The 3D steady-state analysis followed the recommendations of [16–18]. The numerical simulations were based on the so-called Reynolds-Averaged Navier-Stokes (RANS) equations, which are suitable for analyzing mean pressure distribution, discarding any transient flow effect. The applied turbulence model was \( k-\varepsilon \) standard [19], which was selected based on a previous grid sensitivity analysis. The preliminary results showed that the \( k-\varepsilon \) standard turbulence model provides acceptable solutions, which are almost independent of the grid resolution.

The studied wind directions were 0°, 30°, 45°, 60°, and 90°. The CWE analysis was performed using ANSYS-Fluent 2019 R3 [20].

2.3. Domain size dimensions and mesh resolution

The creation of the flow domain with double inlet/outlet faces followed the suggestions presented in [21–23]. The double inlet/outlet allows a more straightforward application in the case of non-orthogonal wind directions. The distance from the structure to the inlet and to the top faces was \( 5H \); to the outlet surfaces was \( 15H \), based on [17, 18].

The semi-structured mesh integrated tetrahedral elements close to the structure and hexahedral elements in the rest of the domain (Fig. 2). Around the membrane surface, inflation layers were also considered. The minimum element size was 0.5 m, whereas the maximum was 5.0 m; the total number of nodes and elements were \( 5.0 \times 10^6 \) and \( 5.5 \times 10^6 \), respectively.

2.4. Boundary conditions and convergence criterion

The following boundary conditions were applied:

a) Inlet face: the inlet velocity profile followed the power law equation (Eq. 1) to characterize a flat type terrain [23–25]:

\[
\frac{U}{U_h} = \left( \frac{Z}{Z_h} \right)^\alpha,
\]

where \( U \) is the wind velocity at a certain point; \( Z \) is the point height; \( Z_h \) is a reference height; and \( U_h \) is the wind velocity at the reference height (15 m s\(^{-1}\)); finally, \( \alpha \) is the velocity exponent that depends on the terrain roughness, based on [23], \( \alpha = 1/9.5 \).

b) Outlet face: 0 Pa gauge pressure;

c) Walls: no-slip, free-slip, or symmetry condition. Additionally, the near-wall treatment was in accordance with
scalable wall functions approximation. The lower $y^+$ limit for those cells near the walls was 30.

For all wind directions, the membrane surface and the ground surface had the no-slip wall condition, whereas the top domain surface had the symmetry condition. The other abovementioned boundary conditions depended on the current wind direction. For example, for the $0^\circ$ wind flow, the inlet boundary was the surface perpendicular to the $Y$-axis on the windward side of the structure. In contrast, the wall on the positive side of the $Y$-axis (and perpendicular to it) was the outlet boundary face. Additionally, for this wind direction, both boundary walls perpendicular to the $X$-axis followed the free-slip boundary condition.

Similarly, for the $90^\circ$ wind direction, the inlet and outlet boundaries were the domain walls perpendicular to $X$-axis. Finally, for oblique wind directions, the $X$ and $Y$ components of the wind velocity vectors were set at the walls on the negative side of the $X$ and $Y$ axes; then, the outlet boundaries were the walls on the positive side. Figure 3 depicts the boundary conditions for orthogonal and oblique wind directions.

The solution method involved the SIMPLEC scheme for the pressure-velocity coupling and second-order spatial discretization. The convergence criterion was a limit of $1 \times 10^{-5}$ for all residuals, but the analyses were stopped if they reached 5,000 iterations.

### 3. RESULTS AND DISCUSSION

This section introduces the results based on CWE simulations and their validation with experimental results. The pressure distributions on the surfaces are described by dimensionless $C_p$ values:

$$C_p = \frac{p - p_0}{\rho U^2/2}, \quad (2)$$

where $p$ is the pressure at a specific point on the membrane surface; $p_0$ is the upstream pressure; $\rho$ is the air density; and $U$ is the free-stream velocity. The notations $C_{p_{WT}}$ and $C_{p_{CWE}}$ mean pressure coefficients on the external and internal surfaces of the structure, respectively (Fig. 1).

The validation included error measurement methods that compared the WT-based and the CWE-based $C_p$ values. The accuracy assessment included the Mean Absolute Error (MAE) and the Mean Square Error (MSE) calculation (Table 1):

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |C_{p,i}^{(WT)} - C_{p,i}^{(CWE)}|, \quad (3)$$

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (C_{p,i}^{(WT)} - C_{p,i}^{(CWE)})^2, \quad (4)$$

where $n$ is the total number of points to compare ($n = 102$ according to the number of measurement points during the WT experiments); $C_{p,WT}$ and $C_{p,CWE}$ are the pressure coefficients based on WT tests and CWE simulation, respectively.

Two sets of measurement points were selected for further comparison. Point set $A$ represents six points on the top and on the bottom of the arches, in the symmetry plane that contains the central axis of the structure. Point set $B$ corresponds to the points on the external and internal surfaces of the two central arches. Figure 4 depicts the pressure coefficients in these set of points on the external surface, and Fig. 5 on the internal one.

Figures 4a and 5a show the $C_p$ in point set $A$ for $0^\circ$ wind direction. The most significant differences between the CWE and WT results were detected at the first arch, close to the flow separation area. CWE provided the best results at the last two arches.

Figures 4b and 5b represent the $C_p$ values in the set of points $A$ for $45^\circ$ wind direction. At most of the points on the internal surface, the numerical solution is accurate. Meanwhile, the most significant difference on the external surface

![Fig. 3. Domain dimensions and boundary conditions for all wind directions](image_url)

![Fig. 4. $C_p$ on the external surface, a) $0^\circ$; b) $45^\circ$; and c) $90^\circ$ wind direction](image_url)
was on the top of the first arch. The large turbulent eddy motions in that area are highly unpredictable.

Figures 4c and 5c depict $C_p$ in the point set $B$ for the 90° wind direction. (The dashed lines represent the $C_p$ of the deformed structure shape; this analysis is introduced in the following section.) On the external surface, CWE gave highly accurate results at the windward side of the model; however, there are significant differences from the WT results at the top of the structure. On the internal surface, there is relatively small wind suction, and the numerical solution underestimated the $C_{pi}$ values.

Figure 6 and Table 2 give a more general view of the pressure distribution. Figure 6 includes the pressure coefficient fields based on CWE results for all analyzed wind directions. Table 2 summarizes the maximum and minimum $C_p$ values for every analyzed wind direction. The following conclusions are drawn.

On the external membrane surface, the most significant suction $C_{pe} = -1.752$ was found at 30° wind direction, whereas the maximum positive $C_{pe} = 0.785$ was found at 90° wind direction. The critical wind direction for the inner membrane surface was 60°, which presented the most

![Fig. 5. $C_p$ on the internal surface, a) 0°; b) 45°; and c) 90° wind direction](image)

![Fig. 6. Pressure coefficient distributions on the external (top) and internal (bottom) surface for all analyzed wind directions](image)
significant suction $C_{pi} = -2.473$ and positive $C_{pi} = 0.785$ as well.

In the case of the 45° wind direction, the largest suction determined by CWE ($C_{pi} = -1.861$) was 56% larger than the $C_{pi}$ at the same point according to the WT ($C_{pi} = -1.196$), which represented the most significant error in the negative pressure coefficients. The most significant error in the positive pressure coefficients was much smaller, approximately 16%.

4. DEFORMED SHAPE WIND ANALYSIS

The large displacements of membrane structures and their effect on the pressure distribution cannot be considered during the conventional WT tests. Previous research proved that the impact of the displacements could be significant on the pressure distribution and on the according membrane forces as well [26].

In the current research, following the method presented in [26], the deformed shape of the structure according to 90° wind direction was determined by the Dynamic Relaxation Method (DRM). During the DRM analysis of the membrane structure the considered dynamic pressure was $= 1.52$ kN/m², recommended by the Mexican Standard [24]. The internal pressure in the inflated arches was $p = 25$ mbar. The warp direction in the membrane was supposed to be “parallel” with the centerline of the inflated arches, and the fill direction was perpendicular to the warp direction. Linear elastic, orthotropic material model was taken into account with the same modulus of elasticity in warp and fill directions ($E_w = E_f = 400$ kN/m, $G = 10$ kN/m). The maximum displacement was approximately 2.7 m, and it was detected at the windward side of the structure. The deformed shape was 3D printed for a second WT test (Fig. 7).

The pressure distribution over the deformed shape was determined by WT test and CWE analysis following the methodology introduced at the analysis of the undeformed structure. MAE and MSE factors show that the CWE analysis provides a good approximation to the experimental results (Table 1).

Table 3 compares the maximum and minimum $C_p$ values, Fig. 8 shows the pressure coefficient fields based on WT test and CWE approach. The results show that there is a significant difference at the top of the structure between the numerical and the experimental results, but with the exception of that area, the CWE results give a good approximation. There is a very good agreement on the windward side of the model, and the results show positive pressure on a significantly larger area on the external surface compared with the undeformed surface (Fig. 5).
5. CONCLUSION

This paper presented the pressure coefficient maps for an open air-inflated membrane structure based on 3D steady-state numerical simulation. The RANS equations with the $k-\varepsilon$ standard turbulence model were used to describe the turbulence flows. The pressure coefficients on the external and internal surfaces were determined for five wind directions. The CWE results were compared with experimental results and the error measurement, based on MAE and MSE factors showed that there is a good general agreement. However, significant, local discrepancies were found in some areas highly influenced by large eddy motions (close to flow separation regions). The analysis of the deformed shape according to one of the analyzed wind directions proved that the effect of the displacements could have a significant impact on the pressure coefficient maps.

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REFERENCES


