

Moving downburst effects on long-span roof structure

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ABSTRACT: Taking the interaction of moving downbursts with buildings into consideration is rather difficult in moving-downbursts-induced structure vibration analysis. By assuming that the jet velocity is proportional to the wind velocity in the fluid field, deterministic-stochastic hybrid model is utilized to generate the fluctuating jet velocity. Consequently, by using the time-varying mean wind pressure coefficients, the wind loading that considers the fluid-structure interaction is attained. Furthermore, the relationship between the mean wind pressure coefficient and the ratio of jet velocity to the translating speed is studied. The comparison of structural dynamics response caused by moving downburst and atmosphere bound layer wind is conducted through a defined downburst factor. It is found that the downburst factor increase with the increment of the structural natural frequency.

KEYWORDS: moving downbursts, CFD simulation, dynamic mesh, wind loading, structural vibration, deterministic-stochastic hybrid model.

1 INTRODUCTION

Thunderstorm downburst is a transient extreme wind, which is a strong downdraft spreading from the center to periphery and occurs during the thunder weather usually. It caused numerous structural destructions worldwide ^[1]. The studies in recent decades had shown that the thunderstorm downbursts would cause a higher near-surface wind velocity than that in atmosphere bound layer (ABL) winds. And the corresponding wind loading caused has gained many attentions.

The characteristic of wind field of steady thunderstorm has achieved comprehensive understanding. Experimental and numerical results those attained by utilizing the impinging wall jet model rather than vortex mode, showed reasonable agreements with the limited full-scale data ^[2-4]. For convenience of wind loading studies, many researchers (e.g. Oseguera and Bowles ^[5], Vicroy ^[6], Wood ^[7], etc.), proposed empirical models to describe the wind profiles. With consideration of wind load caused by moving downbursts, vector summation method and deterministic-stochastic hybrid model (DSHM) are mostly used. The former was proposed by Holmes and Oliver to simulate the mean time history of horizontal wind velocity in a travelling downburst ^[8]. The latter was proposed by Chen and Letchford to simulate the time history of horizontal wind velocity with random fluctuation ^[9]. So far, the study on the wind field of moving thunderstorm and its effects to structure is scarce. By utilizing a moving wall jet experimental device, Letchford and Chay obtained the transient pressure field on a cube immersed in a moving downburst ^[10]. Sengupta contributes to computational fluid dynamics (CFD) study on moving down bursts effecting on buildings by using dynamic mesh method ^[11]. For purpose of using a uniformed equation to consider both gust front wind and conventional wind, Kwon and Kareem presented a new framework of wind loading ^[12].

In this paper, the dynamics of buildings subjected to moving downbursts are studied. The surface wind pressure of buildings, which is obtained by dynamic-mesh-method-based CFD simulation, is utilized to determine wind loading. By assuming that the quasi-steady assumption is satisfied in moving down burst, the fluctuation component of the wind pressure is simulated ac-

ording to DSHM. The structural dynamics caused by moving downbursts are compared with that by ABL winds, through using a designated downburst factor. In addition, the downburst factor varying with the characteristic of structure dynamics and moving downburst are analyzed.

2 DOWNBURST FACTOR

The conventional gust loading factor (G_{GLF}) is defined as

$$G_{GLF} = \frac{\hat{x}_{B-L}}{\bar{x}_{B-L}} \quad (1)$$

where $\hat{x}_{B-L}$ and $\bar{x}_{B-L}$ represent maximum and mean displacement of a structure subjected to ABL wind. G_{DB} is defined as a ratio of maximum displacements in the moving downbursts to that in ABL winds. Thus

$$G_{DB} = \frac{\hat{x}_{DB}(z, t)}{G_{GLF} \cdot \bar{x}_{B-L}(z)} \quad (2)$$

where $\hat{x}_{DB}(z, t)$ is the maximum displacement of a structure subjected to moving downbursts; z and t are height and time respectively.

In order to comparing the downburst factors those computed using different jet velocities V_{jet} , the displacement of structure under the boundary layer wind load is therefore

$$\bar{x}_{B-L}(z) = \left(\frac{V_{jet}}{V_{jet,0}} \right)^2 \bar{x}_{B-L,0}(z) \quad (3)$$

where $\bar{x}_{B-L,0}(z)$ is the displacement of structure subjected to the reference ABL wind; $V_{jet,0}$ is the jet velocity when the wind pressure at the height of 10 m is equal to the reference wind pressure in code.

The displacement of structure under downburst can be decomposed into mean displacement $\bar{x}(z, t)$ and fluctuating displacement $\tilde{x}(z, t)$.

$$x_{DB}(z, t) = \bar{x}_{DB}(z, t) + \tilde{x}_{DB}(z, t) \quad (4)$$

Then, the maximum displacements in the downburst can be rewritten as

$$\hat{x}_{DB}(z, t) \approx \max[\bar{x}_{DB}(z, t)] + \max[\tilde{x}_{DB}(z, t)] \quad (5)$$

By substitution of Equation 6 into Equation 2, we have

$$G_{DB} \approx G_{DB_Sum} = \bar{G}_{DB} + \tilde{G}_{DB} \quad \bar{G}_{DB} = \frac{\max[\bar{x}_{DB}(z, t)]}{G_{GLF} \cdot \bar{x}_{B-L}(z)}, \text{ and } \tilde{G}_{DB} = \frac{\max[\tilde{x}_{DB}(z, t)]}{G_{GLF} \cdot \bar{x}_{B-L}(z)} \quad (6)$$

where $\bar{G}_{DB}$ and $\tilde{G}_{DB}$ are designated as mean and fluctuating downburst factors, respectively; the sum of them is the synthesis downburst factor G_{DB_Sum} .

By using the truncated modes, the displacement has a form of

$$x(z, t) = \phi(z) q(t) = [\phi_1(z), \phi_2(z), \dots, \phi_i(z)] \times [q_1(t), q_2(t), \dots, q_i(t)]^T \quad (7)$$

Where $\phi_i(z)$ is the i th mode; $q_i(t)$ is the corresponding time varying modal displacement. Thus we define the modal-decomposition-based downburst factor $G_{DB,i}^D$ as

$$G_{DB,i}^D = \frac{\max[\phi(z) q_{DB}(t)]}{\phi(z) q_{B-L}} = \frac{\max[\phi_1(z) q_{DB1}(t) + \phi_2(z) q_{DB2}(t) + \dots + \phi_i(z) q_{DBi}(t)]}{\phi_1(z) q_{B-L1} + \phi_2(z) q_{B-L2} + \dots + \phi_i(z) q_{B-Li}} \quad (8)$$

3 NUMERICAL SIMULATION

3.1 Setup and numerical simulation parameters

We utilized Fluent 6.2, which is commercial CFD software, to achieve a numerical approach. The moving downburst with a jet diameter of 500 m is simulated based on impinging wall jet model, as shown in Figure 1. The jet height is equal to the jet diameter. A long span flat roof whose size is $200 \times 200 \times 20$ m (length $\times$ width $\times$ height) is put in the fluid field.

Figure 1 shows the computational model and boundary conditions for downburst simulation. The downburst is modeled as a round jet, impinging onto a flat plate. The size of the three-dimensional computational domain is $18 \times 8 \times 5 D_{jet}$, where D_{jet} is the jet diameter. The downburst is simulated to move a distance of $10 D_{jet}$ in the longitudinal direction.

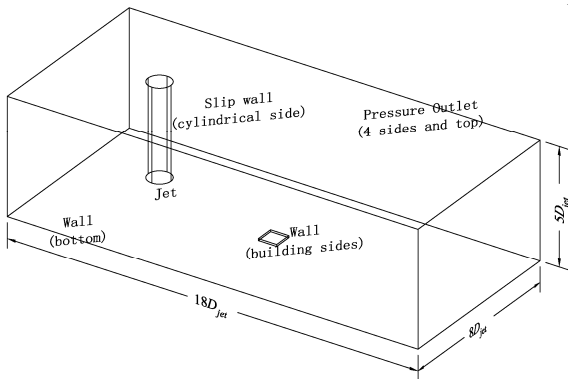


Figure 1. Computational model.

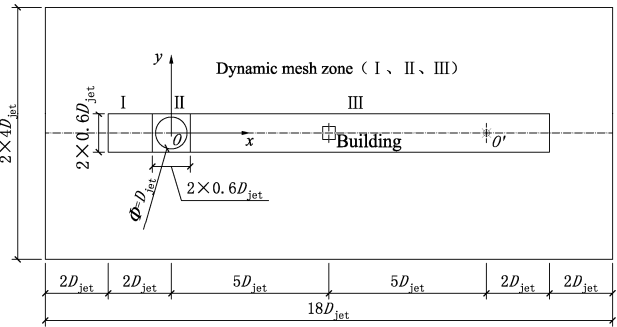


Figure 2. Schematic diagram of dynamic mesh zone.

The dynamic mesh model can be used to simulate the flows where the shape of the domain is changing with the time due to the motion of the boundaries [13]. The motion of the boundary is described by utilizing either boundary profiles, user-defined functions (UDFs), or some specific equations. Based on the motion of boundary, the volume mesh of the domain is automatically updated. Accordingly, the dynamic mesh model is capable of simulating the moving downbursts.

As shown in Figure 2, a dynamic mesh zone is separated from the domain by some non-conformal mesh interface. The dynamic mesh zone is divided into three parts: I, II and III. The part II is a rigid body motioning region, and the others are deforming regions. The velocity of the part II is specified by UDF. In order to study the wind pressure distribution of the roof, the downburst moves from point O to the point O'. Due to the motion of part II, the cells in part I and III would be distorted. The layering method is used to update the volume mesh based on predefined split and collapse factors. The split and collapse factors are 0.4 and 0.4, respectively.

The air density is set to be 1.225 kg/m^3 and viscosity $1.7894 \times 10^{-5} \text{ kg/(m}\cdot\text{s)}$. The RNG k- ϵ model is used to simulate the moving downburst. The default model constants in RNG k- ϵ model are used. For RNG k- ϵ model, the SIMPLE algorithm is used for solving the pressure-velocity

coupling equations. A standard scheme is employed for pressure discretization, and a 1st order upwind scheme is employed for momentum, TKE and TDR. The residual errors for all the variables are set to be 1×10^{-4} , except for continuity 1×10^{-3} .

All grids are structured grids, except for the meshes in part II. Because of the curved boundary in part II, the adaptable unstructured grids are used. For the region near the ground and the building faces, enhanced wall treatment is adopted and a fine mesh is used to ensure the $y^+ \leq 1$. Figure.3 shows the mesh used in this simulation and the local mesh around wall.

The validity of the numerical simulation is verified by using different domain and grid sizes in the steady-state simulations. For unsteady cases, time steps dependency tests are performed and a non-dimensional time steps are chosen.

$$\Delta t^* = V_t \Delta t / D_{\text{jet}} = 0.008 \quad (9)$$

The jet velocity ratio V_{TJ} is defined as the ratio of the jet translating speed V_T to jet velocity V_{jet} . In order to numerically predict the effects of jet velocity ratio of a moving downburst on the roof, two groups of simulations are conducted. In the first group, the jet velocities are kept as 47.5 m/s, and the translating speeds are taken from the followings: 5.0, 10.0, 12.5, 15.0, 17.5, 20.0, 22.5, 23.75, 25.0 m/s. In the other group, the translating speeds are kept as 10.0 m/s, and the jet velocities are varied from the followings: 28.3, 30.0, 40.0, 50.0 m/s.

As shown in the Figure.3, a total of 81 measuring points are uniformly distributed on the roof, and 9 critical measuring points are marked with numbers. The time-varying mean wind pressure coefficient in moving downbursts is defined as

$$\bar{C}_{\text{pi}}(t) = \bar{P}_i(t) / (0.5 \rho V_{\text{jet}}^2) \quad (10)$$

where $\bar{P}_i(t)$ and $\bar{C}_{\text{pi}}(t)$ are mean wind pressure and wind pressure coefficient of the i th measuring point, respectively.

The displacement of downburst is non-dimensionalized by the jet diameter.

$$l^* = V_t t / D_{\text{jet}} \quad (11)$$

where V_t is the translating speed.

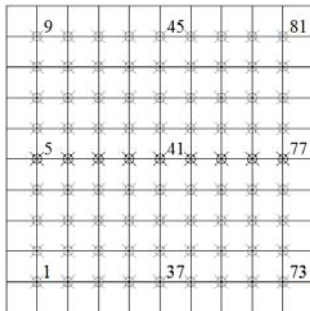


Figure 3. Layout of the measuring points.

3.2 Results

At the initial time, the distance ($r_{\text{D-R}}$) from the center of downburst to the center of roof is $5D_{\text{jet}}$. Then, it would be varied with the motion of the downburst. Consequently, and the mean wind pressure distribution on the roof would be time varying. The mean wind pressure distribution on the roof varied with the motion of downburst is shown in Figure.4.

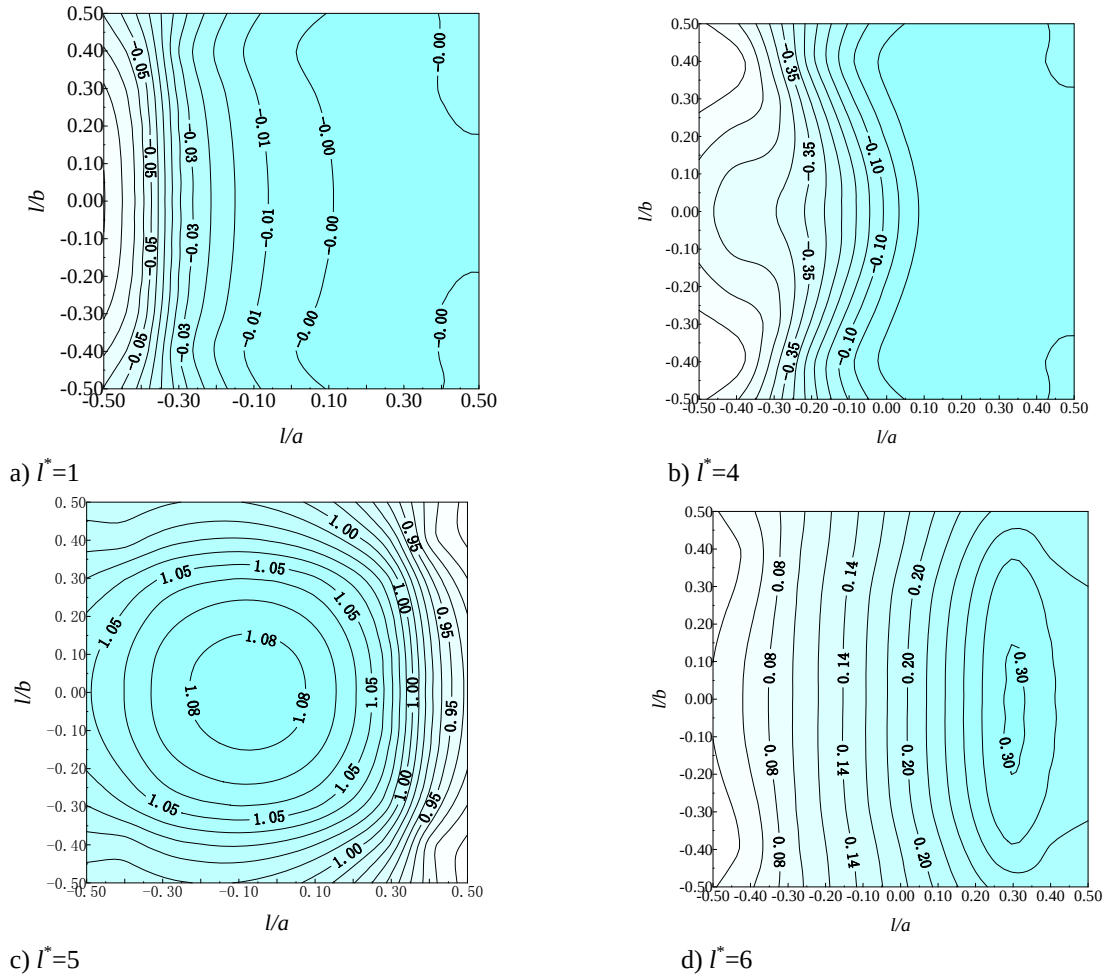


Figure. 4 Wind pressure distribution on the roof

While the downburst travels $1D_{jet}$, the roof is still far away from the downburst. The pressure of the most regions on the roof is nearly zero, whereas there is a relatively large negative pressure in the windward area. While the downburst travels $4D_{jet}$, that is say r_{D-R} is equal to $1D_{jet}$, the pressure distribution is similar to the case of $l^*=1$, but the negative pressure area get bigger and the minimal negative pressure value become smaller. When the downburst travels $4D_{jet}$, the roof is quite under the center of the downburst, and the pressure distribution is significantly different from others. The whole roof is subjected to positive pressure and the maximum value is about 1.0. When the downburst travels $6D_{jet}$, r_{D-R} is again equal to $1D_{jet}$, but the distribution is quite different from the case that $l^*=1$. The values of the pressures in whole roof are positive.

The time histories of mean wind pressures of the measuring points 1, 37, 73 (these three points is on the outmost side line), 5, 41, and 77 (these three points is on the middle line) are chosen to be surveyed. The time histories of mean wind pressure coefficients of all six measuring points for $V_{jet}=47.5$ m/s and $V_t=10.0$ m/s are shown in Figure 5. The trend of all six curves are similar, and they all reach their peak values around $l^*=5.0$.

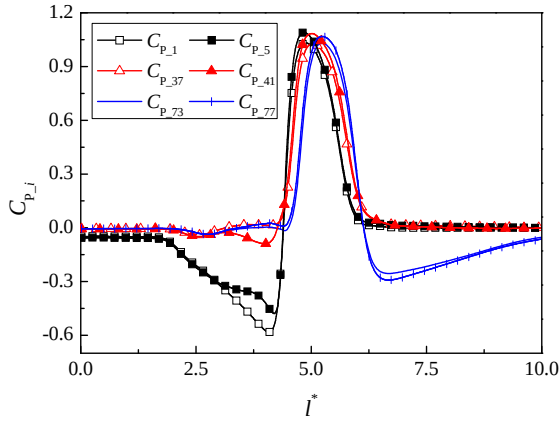


Figure. 5 Time histories of $\bar{C}_{p_i}$.

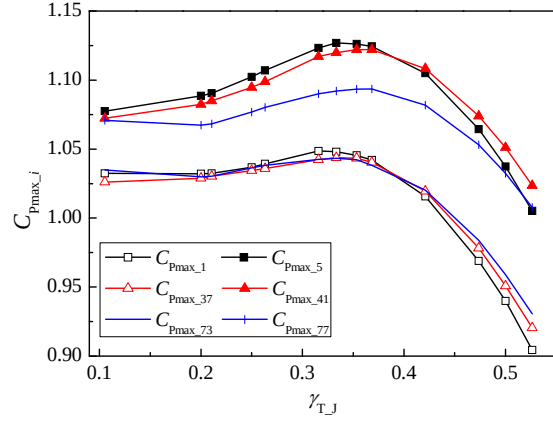


Figure. 6 $\gamma_{T,J}$ versus the peak value of $\bar{C}_{p_i}$.

The relationship between the jet velocity ratios and the peak value of mean pressure coefficient are shown in Figure 6. It is shown that the peak pressure near middle line is greater than that near the side line. The peak pressure increases with the increment of the jet velocity ratio while the jet velocity ratio is less than 0.316. And it decreases in case of that the jet ratio is greater.

4 DYNAMIC RESPONSE OF THE ROOF

4.1 Simulation of wind loading

By using $\bar{C}_{p_i}$, it is easy to achieve the time history of mean wind pressure, according to Equation 10. Nevertheless, in order to conduct structural dynamic analysis, the fluctuation characteristics of wind should be considered. It is assumed that the quasi-steady assumption is still satisfied in a moving downbursts field. Accordingly, the fluctuation component of the wind pressure is proportional to the jet velocity. Thus, we have

$$P_i(t) = 0.5\rho V_j^2 \bar{C}_{p_i}(t) \quad (12)$$

where P_i is the wind pressure of the i th surface zone of the building, and V_j is the jet velocity with fluctuation. Note that the jet velocity is proportional to the wind velocity (or horizontal wind velocity) in the fluid field. It is known, DSHM is capable of simulating the horizontal wind velocity in the fluid field of moving downburst. It assumes that the wind speed could be decomposed into a mean wind speed and a fluctuating wind speed. That is to say

$$U(z,t) = \bar{U}(z,t) + \tilde{U}(z,t) \quad (13)$$

where $U(z,t)$ is the wind speed at position z and time t ; $\bar{U}(z,t)$ is a deterministic function and means the mean wind speed; $\tilde{U}(z,t)$ is the fluctuation with zero mean and a stochastic process.

In DSHM, it is also assumed that the fluctuation can be obtained by a stationary random process multiplied by a modulation function. That is to say

$$\tilde{U}(z,t) = a(z,t)\lambda(z,t) \quad (14)$$

where $a(z,t) = 0.10\bar{U}(z,t)$ and is a modulation function; $\lambda(z,t)$ is a stationary Gaussian stochastic process, and could be numerically generated by utilizing the Kaimal spectrum, as shown in Figure 7.

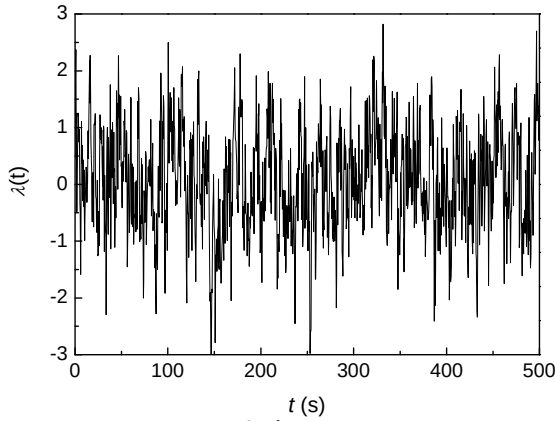


Figure.7 time history of λ .

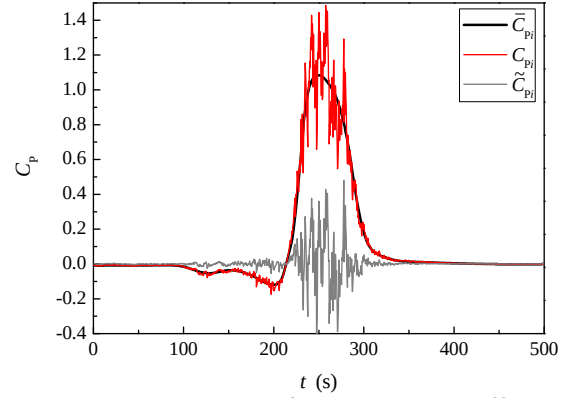


Figure.8 Time histories of wind pressure coefficients.

Note that $U(z,t)$ is proportional to V_j , we have

$$V_j = V_{jet} \cdot [1 + 0.1\lambda(t)] \quad (15)$$

By substituting Equation 15 into Equation 12, the time histories of wind pressure that contains the fluctuation could be attained. Then the wind pressure coefficient would be

$$C_{pi}(t) = P_i(t) / (0.5\rho V_{jet}^2) \quad (16)$$

Figure 8 shows the time histories of three wind pressure coefficient C_{pi} . And the fluctuation wind pressure coefficient in Figure 8 is defined as

$$\tilde{C}_{pi} = C_{pi} - \bar{C}_{pi}. \quad (17)$$

Finally, the concentrated load on the i th node of the roof can be expressed as:

$$F_i(t) = P_i(t) \cdot A_i \quad (18)$$

where A_i is the represented area of the i th node.

4.2 ABL wind load and the finite element model (FEM) of the roof

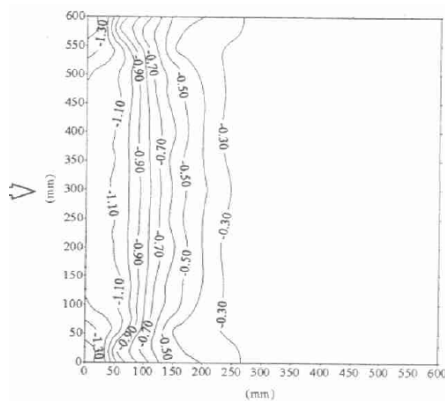


Figure. 9 Wind pressure distribution of the Lu's roof ^[14].

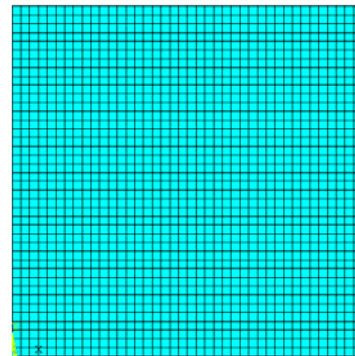


Figure. 10 Element division of the roof.

The result from a rigid model wind tunnel test for a roof, which is conducted by Lu ^[14], is tread as ABL wind load for the roof. The wind pressure distribution of the Lu's roof is shown in the

Figure9. In addition, Lu proposed an empirical estimation of gust loading factor that is a function of the natural frequency of the structure. It is

$$G_{GLF} = -0.1348 f^5 + 1.0241 f^4 - 3.1205 f^3 + 4.855 f^2 - 4.046 f + 2.8668 \quad (19)$$

where f is the natural frequency.

The dynamic response of the roof is analyzed in ANSYS 10.0. The roof is simply supported on four sides, and the effects of primary and secondary beam are ignored. The elastic modulus and Poisson's ratio are, respectively, $3.0 \times 10^{10} \text{ N/m}^2$ and 0.31, and the damping ratio of the roof is 0.05. The roof is divided into 1600 element, by using the shell 63.

According to the shell theory, the frequencies of plate are affected by its thickness and surface density. The thickness and density of the roof are changed to get the different natural frequency. Totally, 9 plates are studied and their natural frequency varied from 0.467 Hz to 2.015 Hz.

4.3 Results and discussion

With consideration of a moving downburst whose jet velocity and translating speed are 47.5 m/s and 10 m/s respectively, the time histories of displacement and acceleration at the middle of the roof are shown in Figure11 and Figure 12 respectively. In case of moving downbursts, larger displacement and acceleration are observed. The parameters of the moving downburst in following Figures 13-16 are fixed at that $V_{jet}=47.5 \text{ m/s}$ and $V_t=10 \text{ m/s}$.

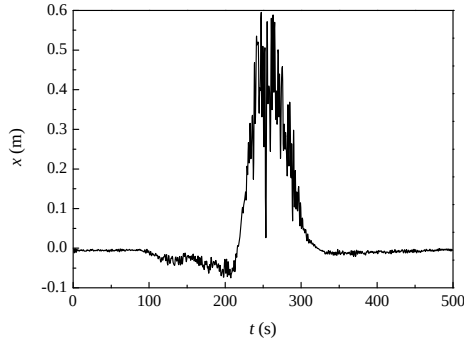


Figure. 11 Time history of the displacement.

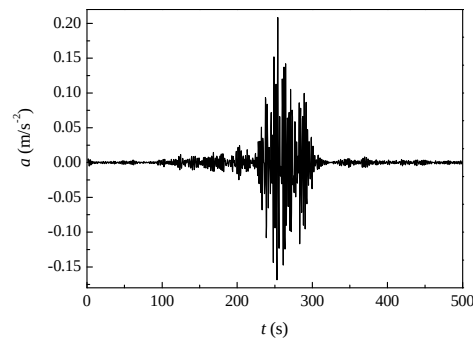


Figure. 12 Time history of the acceleration.

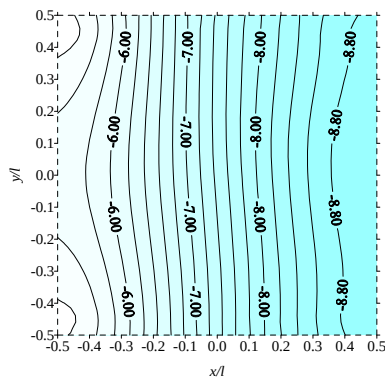


Figure. 13 distribution of G_{DB0} on the roof.

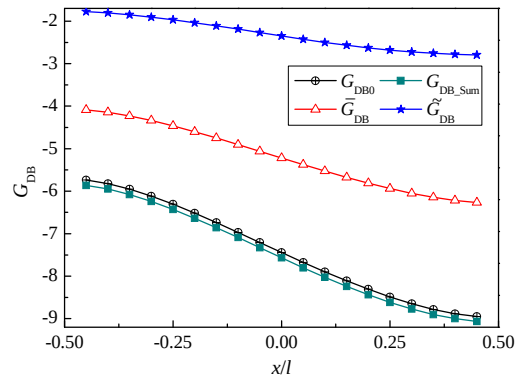


Figure. 14 G_{DB} on the along-wind middle line.

Figure 13 shows the distribution of G_{DB0} on the roof. G_{DB0} is obtained directly according to Equation 2, and is designated as direct downburst factor. Figure 14 shows four kinds of downburst factors of the along-wind middle line. The four downburst factors increase with the in-

crease of x , and the synthesis downburst factor is close to the direct downburst factor. So the dynamic response of downburst on structure could be decomposed into two parts: mean and fluctuation. Additionally, the absolute value of the direct downburst factor are quit larger than 1. It means that the effect of the moving downburst is quit larger than that of ABL wind.

Figure.15 shows the distribution of G_{DB0} and G_{DBi}^D on the along-wind middle line. The G_{DB1}^D is a constant at any point. With the increase of the order, the G_{DBi}^D gets closer to the G_{DB0} . The curves of G_{DBi}^D intersect at the middle point of the roof ($x/l=0$). It means that using the first mode would accurately capture the factor for the center point, whereas first four modes should be taken into consideration for the other locations.

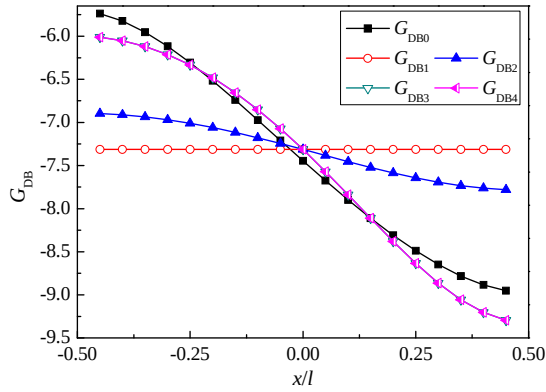


Figure. 15 Comparisons of G_{DB0} and $G_{DBi}^D(z)$.

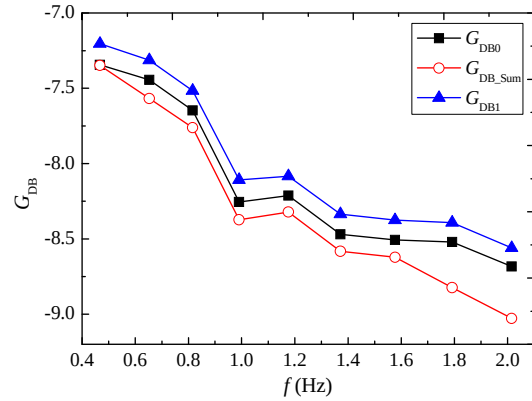


Figure. 16 G_{DB} Varied with natural frequency.

Figure.16 shows the variation of G_{DB0} , G_{DB_Sum} and G_{DB1}^D , at the middle point of the roof, with the natural frequency of the roof. It is observed all three downburst factors increase with the increasing of natural frequency.

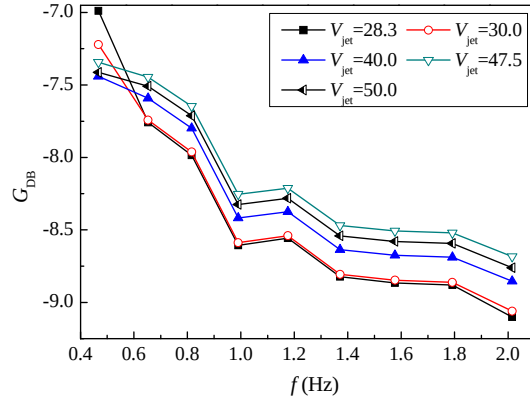


Figure. 17 G_{DB0} varied with jet velocities

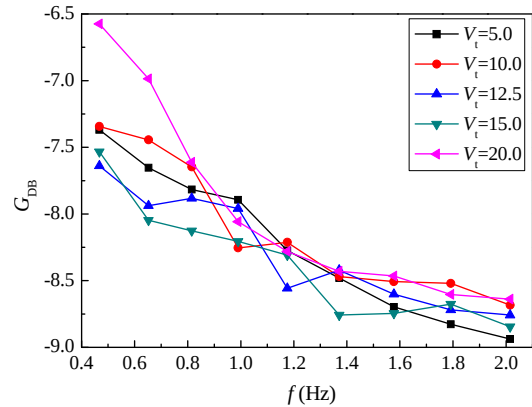


Figure. 18 G_{DB0} varied with translating speeds

Fixing the translating speed at $V_t=10$ m/s, Figure 17 shows the variation of G_{DB0} of the center-point with jet velocities and the natural frequency of the roof. The absolute value of downburst factor increases slightly with the increase of V_{jet} in a range of 28.3 to 50 m/s. Also it increases with the increasing of natural frequency.

Fixing jet velocity at $V_{jet}=47.5$ m/s, Figure18 shows the varying of G_{DB0} of the center-point with the natural frequency of the roof. The absolute value of downburst factor increases with the increasing of natural frequency, whereas it has little correlation with the translating speed.

5 CONCLUSIONS

In the determination of the wind loading, the wind pressure on the building surface, which is acquired through numerical moving downbursts test, is employed directly. For the purpose of ensuring that the simulated fluctuation component of wind velocity coincides with the field observation, it is assumed that the quasi-steady assumption is satisfied during the simulation of fluctuation component of the wind pressure. Accordingly, the wind pressure simulated would more accurately represent the fluid-structure interaction.

The variation of the wind pressure distribution on the roof with the moving of the downburst is surveyed. It is found that the wind pressure would reach its peak value in case of the center of the roof coinciding with the center of downburst. It is also found that the maximum wind pressure coefficient is merely related to the ratio of jet velocity ratio to translating speed.

In order to compare the results with that obtained from ABL wind, the downburst factor, which is the ratio of the maximum displacement response due to moving downbursts to that due to ABL wind, is introduced. The study revealed that using first four modes would satisfy the accuracy requirement in downburst factor computing, whereas first one mode merely could be utilized to computing the downburst factor of the center-point of the roof. It is found the downburst factor is in a range of 6.5 to 9.0, which means that a moving downburst would cause a serious vertical response. Furthermore, the factor would increase with the increment of the natural frequency of the structure.

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