NUMERICAL SIMULATION OF DOWNBURST WIND LOADS USING MODIFIED OBV MODEL

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ABSTRACT

Downburst is an outburst strong wind on or near the ground, and its field characteristics are significantly different from boundary layer winds. The paper discussed a good prospective numerical simulation method of the downburst wind loads based on the previous research. According to the full-scale data from radar observations, the intensity factor $\Pi$ and time dependent radius $r_t$ in the modified OBV model were discussed, and finally the form and way to take their values were presented. Subsequently, the impacts of two aforesaid parameters at the wind speed time histories of downbursts simulation were investigated. Firstly, the wind speed was expressed as the sum of an instantaneous mean wind speed and an amplitude-modulating non-stationary fluctuating wind speed. Secondly, a good prospective method based on the modified Oseguera and Bowles/Vicroy (OBV) model to simulate the mean wind was presented and the fluctuating wind was simulated by a modified harmony superposition method. The method contains the effect of the translational motion and the time-dependent decay of the storm. Good agreement is achieved between data from the method and full-scale data from a high intensity downburst that occurred at Andrews Air Force Base in 1983.

KEYWORDS: DOWNBURST, WIND LOADS, WIND SPEED TIME HISTORIES, MODIFIED OBV MODEL, HARMONY SUPERPOSITION METHOD

1 Introduction

[Fujita (1985)] defined downburst as a strong downdraft which induces an outburst of damaging winds on or near the ground. Numerous structural failures caused by downburst have been recorded around the world, such as in Australia, the United States and Japan [Holmes (1999)]. [Whittingham (1964)] recognized the importance of thunderstorms in the Australian extreme wind climate in the early 1960s. [Melbourne (1972)] alluded to their importance as design wind events. In recent years the downbursts have been concerned actively in the field of world structural wind engineering [Letchford, Mans and Chay (2002)]. In order to study the responses of the structures under the downburst wind loads in the time domain, it needs to acquire the wind speed time histories of downburst.

Given the randomness of the occurring region and the complexity of wind field characteristics, the full-scale field measurements and the laboratory physical simulations can not provide the wind speed time histories handily. Numerical simulations based on Computational Fluid Dynamics (CFD) have shown good prospects for the research on the downbursts, but several pivotal pre-requisite parameters, such as the initial diameter, the initial altitude and the initial velocity of the downdraft can not be determined precisely at present. According to the current researches [Lizhong and Letchford (2004)] [Chay, Albermani and Wilson (2006)], the numerical simulations using the downburst wind speed analytical models is an efficient method to acquire the wind speed time histories of downbursts.

In this paper, a good prospective numerical simulation method of the downburst wind loads based on the previous research is discussed. According to the radar observations
full-scale data, the intensity factor $\Pi$ and time dependent radius $r_i$ in the modified OBV model were discussed, and finally the form and way to take their values were presented. Subsequently, the impacts of two aforesaid parameters at the wind speed time histories of downbursts simulation were investigated.

2 Wind speed of downburst

In the atmospheric boundary layer, the wind speed of any time at any height can be expressed as the sum of a mean speed and a fluctuating speed:

$$U(z,t)=\bar{U}(z)+u(z,t)$$  (1)

where $\bar{U}(z)$ is a function of height $z$; $u(z,t)$ is a function of height $z$ and time $t$.

Similarly, the wind speed of downburst at any location in space and time can be thought as a mean component vary with time and a fluctuating component:

$$U(x,y,z,t)=\bar{U}(x,y,z,t)+u(x,y,z,t)$$  (2)

where $\bar{U}(x,y,z,t)$ is a function of positions $x,y,z$ with respect to the storm and time $t$, which can be regarded as a mean wind speed varying with time and (for short named mean speed in this paper); $u(x,y,z,t)$ is a stochastic process, which can be regarded as the fluctuating wind speed.

It should be pointed out that a downburst is a non-stationary stochastic process. The fluctuating wind speed of downburst will not necessarily obey a Gaussian distribution, but here we assume that it obeys a Gaussian distribution with zero mean.

3 The simulation of mean wind speed

3.1 The simulation method using the vertical profile and the time function

This method was proposed by [Lizhong and Letchford (2004)]. The mean wind speed of any time at any height can be factorized as the product of a vertical profile and a time function as:

$$\bar{U}(z,t)=V(z)\times f(t)$$  (3)

It is assumed that the mean wind speed of any time at any height can reach its maximum value simultaneously at some time when the time function $f(t)$ is equal to 1. The time function $f(t)$ in Eq.(3) describes the way the mean wind speed evolves with time. With ignoring the direction of wind speed $f(t)$ is defined by

$$f(t)=\frac{|V_r(t)|}{\max|V_r(t)|}$$  (4)

where $V_r(t)$ is the wind velocity vector combing the vector of the radial impinging jet velocity and the storm translation speed.

The simulated time history of the combined wind speed and the time function using this method by [Lizhong and Letchford (2004)] are shown in Fig.1.
3.2 The modified OBV model

[Oseguera and Bowles (1988)] developed an axisymmetric analytical model for the non-turbulent winds of a stationary downburst based on mass continuity equations. The radial ($U_r$) and vertical ($U_z$) velocities are given by the equations:

$$ U_r(r,z) = \frac{\lambda R^2}{2r} \left[ 1 - e^{-(r/\lambda)} \right] e^{-\left( z/\left( z_*/(r^2) \right) \right)} $$

$$ U_z(r,z) = -\lambda e^{-(r/\lambda)} \left[ e^{\left( z/\epsilon \right)} - 1 \right] \cdot z \left( e^{\left( z/\epsilon \right)} - 1 \right) $$

where $\lambda$ is a scaling factor, s\(^{-1}\); $R$ is radius of downburst, m; $r$ is radial coordinate (distance from downburst center), m; $z$ is altitude above ground, m; $z_*$ is characteristic height, out of boundary layer, m; $\epsilon$ is characteristic height, in boundary layer, m.

[Vicroy (1991)] modified the Oseguera and Bowles model by defining a new shaping function that the model more accurately matched the horizontal wind profile characteristics of a downburst. Then, the radial ($U_r$) and vertical ($U_z$) velocities take the forms:

$$ U_r(r,z) = \frac{\lambda R^2}{2r} \left[ e^{\left( z/\left( z_*/(r^2) \right) \right)} - e^{\left( 2z/\left( z_*/(r^2) \right) \right)} \right] e^{\left( z/\left( z_*/(r^2) \right) \right)} $$

$$ U_z(r,z) = -\lambda \left[ \frac{z}{c_1} \left( e^{\left( z/\left( z_*/(r^2) \right) \right)} - 1 \right) - \frac{z}{c_2} \left( e^{\left( 2z/\left( z_*/(r^2) \right) \right)} - 1 \right) \right] \cdot \left[ \frac{1}{2} \frac{r^2}{\epsilon^2} \right] \cdot e^{\left( z/\left( z_*/(r^2) \right) \right)} $$

where $\alpha$, $c_1$ and $c_2$ are model constants, [Vicroy(1992)] recommended that $c_1 = -0.15$ , $c_2 = -3.275$ and $\alpha = 2$ ; $r_\text{p}$ is the radius where the maximum velocity reached, $m$ ; $z_m$ is the height where the maximum velocity reached, $m$ ; the other parameters have same significance with Eq.(6) and Eq.(7). Here scaling factor $\lambda$ is defined as:

$$ \lambda = \frac{2U_{r,\text{max}}}{r_\text{p}} \left[ \frac{1}{e^{2\epsilon}} \right] $$

Thanks to the modification the model can describe the horizontal wind of a downburst more accurately. Therefore the model is named as the Oseguera and Bowles/Vicroy model (short for the OBV model).

[Chay, Albermani and Wilson (2006)] put forward two important changes for the OBV model, including: (1) considering the effect of the storm’s translational motion; (2) considering the time dependency of storm strength. The radial ($U_r$) and vertical ($U_z$) velocities in the modified OBV model are expressed as:

$$ U_r(x,y,z,t) = \Pi U_{r,\text{max}} r \left[ e^{\left( z/\left( z_*/(r^2) \right) \right)} - e^{\left( 2z/\left( z_*/(r^2) \right) \right)} \right] e^{\left( z/\left( z_*/(r^2) \right) \right)} $$

$$ U_z(x,y,z,t) = -2 \Pi U_{r,\text{max}} z_m \left[ \frac{1}{c_1} \left( e^{\left( z/\left( z_*/(r^2) \right) \right)} - 1 \right) - \frac{1}{c_2} \left( e^{\left( 2z/\left( z_*/(r^2) \right) \right)} - 1 \right) \right] \cdot \left[ \frac{1}{2} \frac{r^2}{\epsilon^2} \right] \cdot e^{\left( z/\left( z_*/(r^2) \right) \right)} $$

where $\Pi$ is the intensity factor; $U_{r,\text{max}}$ is the maximum radial velocity, $\text{ms}^{-1}$ ; $r$ is the radial distance from the storm centre, m; $r$ is the time dependent radius at which the maximum outflow speed occurs, $m$ ; $z$ is the elevation, $m$ ; $r_p$ is the radius to maximum outflow speed at $\Pi = 1$, $m$ ; $z$ is the elevation of maximum speed at any radial position, $m$ ; $U_{\text{trans}}$ is the translational velocity of the storm, $\text{ms}^{-1}$ ; $\alpha$, $c_1$ and $c_2$ are model constants, $c_1 = -0.15$ , $c_2 = -3.275$ and $\alpha = 2$. 
3.3 Taking value for the intensity factor $\Pi$ and time dependent radius $r_t$

The wind speeds in the modified OBV model are a function of spatial position coordinates $x, y, z$ and time $t$. The wind speed occurring at any point in space and time can be defined based on this model. It should be pointed out that, (1) the intensity factor $\Pi$ and $\overline{U_{r, \text{max}}}$ should be defined according to the actually observed data; (2) the regulations to describe $r_t$ and $z_r$ is not very clear as yet. It needs more full-scale data and more deeply study.

As for the intensity factor $\Pi$, here we considered that it would take the form as:

$$
\Pi = \begin{cases} 
\frac{t}{T_{\text{max}}} & 0 \leq t \leq T_{\text{max}} \\
\frac{e^{-\left(\frac{t}{T_{\text{total}}}\right)}}{t > T_{\text{max}}}
\end{cases}
$$

(12)

where $T_{\text{max}}$ is the time which the downburst reached maximum velocity, $s$; $T_{\text{total}}$ is the whole time which the downburst continued, $s$.

There is good agreement between this function with representative values and the radar observations described by [Hjelmfelt (1988)], where $T_{\text{total}} = 20$ minutes and $T_{\text{max}} = 5$ minutes as shown in Fig.3.

As for the time dependent radius $r_t$, [Hjelmfelt (1988)] found that the diameter grows nearly linearly at first as the microburst strengthens to maximum intensity and after this initial growth, many microbursts exhibit nearly constant size until dissipation by means of analyzing the radar observed full-scale data. Consequently, here we could assume that $r_t$ increases linearly from some value at the start of the event with some rate.

3.4 The simulation method using the modified OBV model

In order to compare two methods, the same geometric parameters used by [Lizhong and Letchford (2004)] were employed to simulate the mean wind speed herein. The model was configured with $\overline{U_{r, \text{max}}} = 80m/s$, $r_0 = 1000m$, $(d_0, e) = (3000,150)$, $\overline{U_{\text{max}}} = 12m/s$ and $T_{\text{total}} = 500s$. And assumed that the downburst reached its maximum velocity at $T_{\text{max}} = 150s$, $r_t$ equal to 750 $m$ at the start of the event and increasing linearly to 1000 $m$ during 500 $s$ and $z_m = 80m$. The mean wind speeds were simulated at four conditions: condition I, $\Pi = 1$, $r_t = r_p$, condition II, $\Pi = \Pi(t)$, $r_t = r_p$, condition III, $\Pi = 1$, $r_t = r_p$ and condition IV, $\Pi = \Pi(t)$, $r_t = r_p$.

The results are shown in Fig.2. The result on condition I is highly similar with [Lizhong and Letchford (2004)] (see Fig.1). It reveals that the method adopted in this paper can obtain the same results with the [Lizhong and Letchford (2004)] on the condition assumptions. Compared with condition I, the time when the first and secondary peaks occurred is basically identical, but the value of secondary peak is obviously smaller on condition II; the values of the first and secondary peaks are approximately unanimous, but the time interval between the first and secondary peaks is shorter and the first peak delays to occur on condition III; the intensity factor $\Pi$ and the time dependent radius $r_t$ are all taken into consideration on condition IV.

4 The simulation of fluctuating wind speed

The harmony superposition method with introducing fast Fourier transform (FFT)
technique was applied to simulate the fluctuating wind speed.

The fluctuating wind speeds of downbursts are stochastic processes. According to [Lizhong and Letchford (2004)], the wind speed fluctuation can be obtained by amplitude modulating the process:

\[ u(x, y, z, t) = a(x, y, z, t)k(x, y, z, t) \]

where \( a(x, y, z, t) \) is the modulation function, \( a(x, y, z, t) = \eta U(x, y, z, t) \), \( \eta = 0.08 \sim 0.11 \), \( k(x, y, z, t) \) is a stationary Gaussian stochastic process with standard deviation of 1.

Considering that \( k(x, y, z, t) \) obeys the normal distribution, the normalized Kaimal spectrum \( \Phi(z, \omega) \) [Kaimal et al. (1972)] was adopted to express its power spectral density function (PSD). Thus, stochastic process of fluctuating wind speed \( u(x, y, z, t) \) was converted to a uniformly modulated stochastic process, whose PSD is:

\[ S_{\alpha}(x, y, z, t, \omega) = |a(x, y, z, t)|^2 \times \Phi(z, \omega) \]

We assumed that spatial coherence was taken into only in \( z \) (height) directions here, and the coherence function is \( \gamma(z, z', \omega) \), then the power spectral density function of the wind speed time histories acting on structure is expressed as:

\[ S(t, \omega) = \Phi(\omega) \tilde{A}^T(\omega) \]

where \( \Phi(\omega) \) is the PSD matrix of the vector process \( k(z, t) = [k(z_1, t), k(z_2, t), ..., k(z_n, t)]^T \); \( \Phi_{ii}(\omega) = \Phi(z, \omega), i = 1, 2, ..., n \); \( \Phi_{ij}(\omega) = \gamma(z_i - z_j) \times \sqrt{\Phi(z, \omega)\Phi(z, \omega)}, i, j = 1, 2, ..., n, i \neq j \).

By Cholesky factorization, \( \Phi(\omega) \) can be represented as:

\[ \Phi(\omega) = H(\omega)\tilde{H}(\omega)^T \]

If we define \( H_{jk}(\omega) = |H_{jk}(\omega)|e^{i\theta_{jk}(\omega)}, j = 1, 2, ..., n; k = 1, 2, ..., j; i \geq k \)

where \( \theta_{jk}(\omega) = \tan^{-1}\left\{ \text{Im}[H_{jk}(\omega)]/\text{Re}[H_{jk}(\omega)] \right\} \). Then, the stochastic \( k(z, t), j = 1, 2, ..., n \), can be express as:

\[ k(z, t) = \sum_{m=1}^{j} \sum_{l=1}^{N} H_{jm}(\omega) \sqrt{2\Delta\omega \cos[\omega_{ml} t - \theta_{jm}(\omega_{ml}) + \psi_{ml}]} \]

where \( \omega_{ml} = (l-1)\Delta\omega + m\Delta\omega / n, m = 1, 2, ..., n; l = 1, 2, ..., N \); \( \psi_{m1}, \psi_{m2}, ..., \psi_{mn} \) are independent random phase angles distributed uniformly over the interval \([0, 2\pi]\).

At this stage, the wind speed time histories which satisfy the given power spectral density function can be obtained, provided that the power spectral density function of \( k(z, t) \) is designated. It needs to be pointed out that positive integer \( N \) should be taken sufficiently large in order to avoid the result of distortion; and the time increment must be small enough, or else be the part of high-frequency filter.

When we make multi-dimensional numerical simulation, calculating the \( k(z, t) \) using Eq. (18) is extremely time-consuming. Thus, we can introduce the fast Fourier transform (FFT) technique to enhance the computation efficiency. Then, Eq. (18) can be rewritten as follows:

\[ k(z, p\Delta t) = \text{Re} \left\{ \sum_{m=1}^{M} \sum_{n=1}^{M} g^{(i)}_{jm}(q\Delta t) \exp \left( i \left( \frac{m\Delta\omega}{n} \right)(p\Delta t) \right) \right\}, j = 1, 2, ..., n; p = 0, 1, 2, ..., n \times M - 1; \]

where \( q = p / M \); \( M = 2N \);

\[ g^{(i)}_{jm}(q\Delta t) = \sum_{l=0}^{M-1} B_{jm}(l\Delta\omega) \exp(i((l\Delta\omega)(q\Delta t))), q = 0, 1, ..., M - 1 \]

where
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\[ B_{jm}(l \Delta \omega) = \begin{cases} 2H_{jm} \left( l \Delta \omega + \frac{m \Delta \omega}{n} \right) \cdot \sqrt{\Delta \omega} \cdot \exp \left( -i \theta_{jm} \left( l \Delta \omega + \frac{m \Delta \omega}{n} \right) \right) \cdot \exp(i \phi_i^j) , & 0 \leq l \leq N \\ 0, & N \leq l \leq M \end{cases} \]  

(21)

5 Case study

The full-scale data of the downbursts is extraordinarily rare up to the present, and one of the most famous records is that which struck Andrews Air Force Base near Washington, DC, on August 1, 1983 (called AAFB record for short in the following) [Fujita (1985)]. The AAFB record was recorded by an anemograph, which the peak gust was in excess of 130kts at 4.9m above ground (see Fig.4 (a)). For purposes of comparison, the AAFB record was reproduced here with the International System of Units (SI Unit) in Cartesian coordinate system in Fig.4 (b).

The method using the modified OBV model discussed above was employed to simulate the AAFB record wind speed time history. The numerical simulation was conducted with \( c_1 = -0.15 \), \( c_2 = -3.275 \), \( \bar{U}_{r,\text{max}} = 120 \text{ m/s} \), \( \bar{U}_{\text{trans}} = 8 \text{ m/s} \), \( a(x,y,z,t) = 0.11 \bar{U}(x,y,z,t) \), \( r_p = 1000 \text{ m} \), \( (d_p,e) = (7500,150) \), and with assumption that the downburst bursts at \( t = 645 \text{ s} \), then the flow reaches maximum intensity in \( 180 \text{ s} \) after the outbreak and the \( r_t \) equal to \( 750 \text{ m} \) at \( t = 645 \text{ s} \) and increases linearly at \( 0.5 \text{ m/s} \). The fluctuating wind speed was simulated using the harmony superposition method with introducing fast Fourier transform (FFT) technique. The wind speed time histories were simulated under four conditions:

- Condition I, \( \Pi = 1 \), \( r_t = r_p \), without both considering the time-dependent decay of the storm and the effect of the radius to maximum wind speed varying with time;
- Condition II, \( \Pi = \Pi(t) \), \( r_t = r_p \), with considering the time-dependent decay of the storm but without considering the effect of the radius to maximum wind speed varying with time;
- Condition III, \( \Pi = 1 \), \( r_t = r_t \), without considering the time-dependent decay of the storm but with considering the effect of the radius to maximum wind speed varying with time;
- Condition IV, \( \Pi = \Pi(t) \), \( r_t = r_t \), with both considering the time-dependent decay of the storm and the effect of the radius to maximum wind speed varying with time;

The results are shown in Fig.5. Comparing with AAFB record, the time of the first and secondary wind peaks occurred are not fit and the secondary wind peak is overestimated on condition I; the values of the first and secondary peaks are approximately unanimous but the secondary peak delays to occur on condition II; the time of the first and secondary wind peaks occurred are fit well but the secondary wind peak is overestimated on condition III; the result of condition IV displays much better consistent with the full-scale record, and
overcomes the existing problems that the time of the first and secondary wind peaks occurring is not fit and the secondary wind peak is overestimated on the other conditions.

6 Conclusions

In this paper, a good prospective numerical simulation method of the downburst wind loads based on the modified OBV model is discussed. According to the radar observations full-scale data, the intensity factor $\Pi$ and time dependent radius $r_t$ in the modified OBV model were discussed, and finally the form and way to take their values were presented. Subsequently, the impacts of two aforesaid parameters at the wind speed time histories of downbursts simulation were investigated. Good agreement is achieved between data from the method and full-scale data from a high intensity downburst which occurred at Andrews Air Force Base in 1983. The method contains the effect of the translational motion and the time-dependent decay of the storm and describes the downburst process more accurately. The wind speed time history simulated based on this method displays much better consistent with the full-scale record, and overcomes the existing problems that the time of the first and secondary wind peaks occurring is not fit and the secondary wind peak is overestimated on the other conditions. The parameters included in the modified OBV model require more full-scale datas to be defined precisely.
References


