Real-time Simulation of Large Aircraft Flying Through Microburst Wind Field

Gao Zhenxing*, Gu Hongbin, Liu Hui

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

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Abstract

This article deals with real-time hi-fi simulation of large aircraft flying in turbulent wind in a simulator to study its takeoff and landing behavior in microburst wind shear. A parameterized three-dimensional (3D) microburst model is built up on the basis of vortex ring and Rankine vortex principle. Complicated microburst wind fields are simulated by means of vortex ring declination and multi-vortex superposition. Based on the modeling data of Boeing 747-100, a dynamic model with wind shear effects considered is established and a general method to modify the aerodynamic model is proposed. A controller for longitudinal and lateral escapes is designed and verified in simulated microburst wind field. Results indicate that, with high extensibility, reasonability and effectiveness, the 3D microburst model with wind shear effects considered is fit to simulate real wind fields. Different escape schemes can be adopted to fly through a wind field from different locations. The model can be used for real-time flight simulation in a flight simulator.

Keywords: flight simulation; large aircraft; microburst; wind shear; equations of motion

1. Introduction

Low-altitude wind shear means variation of wind direction and velocity[1]. As a kind of low-altitude wind shear, the microburst is caused by strong downdraft from thunderstorm and spreads out near the ground to produce a severe wind shear[2]. With an outburst dimension less than 4 km, a microburst would make aircraft face deadly dangers during takeoff and landing if it does take place in the vicinity of an airport.

During its landing, an aircraft encounters a headwind, which causes lift to increase making it fly above a glide slope. The pilot may decrease the throttle trying to keep it on the slope. At this time, if the aircraft encounters a strong downdraft and subsequent tailwind, with inadequate thrust and low airspeed, it would run the risk of crash. Especially, for a large aircraft with huge mass and inertia, a mistake made by the pilot, be it ever so minor, might lead to a catastrophic disaster because of its unresponsive engine and difficulty in swiftly changing state[1]. In tackling with the threat to safety, modern flight simulators provide various weather conditions to improve pilots’ ability to handle the acute problems created by airflow’s sudden aberrant changes.

In order to build up a real-time simulation model flying through microburst wind field, it is necessary to develop a microburst dynamic model, which should take wind effects into account. Previously, an aircraft was often simplified into a point of mass and the longitudinal escape scheme was studied with a two-dimensional (2D) microburst model. The Federal Aviation Administration (FAA) has proposed three kinds of escape schemes[4]. Recently, researchers have studied a variety of schemes for longitudinal escape based on optimal control and intellectual control methodology[5-6]. Actually, an aircraft does not necessarily reach the center of microburst during landing or takeoff because it is feasible for the plane to leave the wind field from the weaker side of wind shear under the guidance of an airborne wind shear alert system[5,7]. As a result, it is required to devise a three-dimensional (3D) microburst model as well as a 6-degree of freedom (DOF) flight dynamic model with wind effects considered. For large aircraft, their scale of fuselage and wingspan is comparable with that of medium or small wind field with the wind vectors varying across the fuselage and wingspan[8]. Therefore, wind gradient effects on the aircraft motion should be taken into consideration.

There are three methods to model microburst. Of them, the first is to establish a local and temporal wind field database through measurements, such as JAWS[9].
The second is to simulate the whole wind field from the beginning to the end based on atmosphere dynamics\cite{12}\cite{10}, which, however, is not fit for real-time simulation due to the complexities of its solution. The third is to work out engineering models inclusive of fitting model and fluid dynamic model. As a 2D model in essence, the fitting model can only yield an axisymmetric wind field\cite{12}\cite{13}. Fluid dynamic models include doublet sheet model\cite{12}, vortex section model\cite{13}, vortex ring model\cite{14}, etc., which are all of 3D type suitable for hi-fi real-time simulation and can be constructed based on fluid dynamic models.

After proposing a 3D microburst model on the basis of vortex ring and Rankine vortex principle and summarizing several parameters, this article extends it with vortex ring declination and multi-vortex superposition. Then, a 6-DOF dynamic model considering wind shear effects is derived, and, based on modeling data of Boeing 747-100, its modification method considering wind gradient effects is put forward. Finally, a controller for longitudinal and lateral escapes is designed and simulated after preliminary verification of the model.

2. Modeling of Microburst Wind Field

In fluid dynamic models of microburst, there is an essential affinity between doublet sheet model and vortex ring model. However, an awful lot of time should be spent implementing integration for the former\cite{12}. Vortex section model is only an approximation to vortex ring model\cite{13}. The microburst vortex ring model itself is deficient in deviating from the true wind field on central axis and in vortex core. This article begins with introducing the principles of constructing vortex ring model and ends with suggesting a modification method to fit the model for the true wind field.

2.1. Modeling with vortex ring

In Fig.1, a primary ring with the strength of \( \Gamma \) is placed above the ground while an imaginary ring with \( -\Gamma \) below the ground symmetrically.

As shown in Fig.1, in the runway-oriented coordinate system of \( Ox_{yz} \), the primary ring coordinate, \( Ox_{y_{p}z_{p}} \), with the origin, \( O(x_{p}, y_{p}, z_{p}) \), and the imaginary ring coordinate, \( Ox_{y_{i}z_{i}} \), with the origin, \( O(x_{i}, y_{i}, -z_{i}) \), are built up respectively. The radius of both rings is \( R \), and \( M(x_{i,6}, y_{i,6}, z_{i,6}) \) a reference point. Fig.1 shows that the ring planes are not parallel to the ground. When both ring planes are parallel to the ground, the angle \( \theta = 0, \phi = 0 \), the stream function of point \( M \) is\cite{14}

\[
\psi = \psi_{r} + \psi_{\Gamma} = -\frac{\Gamma}{2\pi} \left[ \frac{0.788k^{2}(r_{1} + r_{2})}{0.25 + 0.75\sqrt{1-k^{2}}} \right] - \frac{0.788k^{2}(r_{1} + r_{2})}{0.25 + 0.75\sqrt{1-k^{2}}}
\]

(1) where \( \psi_{r} \) and \( \psi_{\Gamma} \) denote the Stokes’ stream function of the primary ring and the imaginary ring, \( r_{1} \) and \( r_{2} \) the nearest and the farthest distance of the point \( M \) to the primary ring while \( k = r_{2} - r_{1} / (r_{2} + r_{1}) \), \( k' \), \( r_{1}' \), \( r_{2}' \) are parameters pertinent to the imaginary ring. By derivation of Eq.(1), the induced velocities of point \( M \) can be obtained:

\[
W_{x} = \left( \frac{x_{M} - x_{p}}{r_{M}^{2}} \right) \frac{\partial \psi}{\partial x_{M}}
\]

(2)

\[
W_{y} = \left( \frac{y_{M} - y_{p}}{r_{M}^{2}} \right) \frac{\partial \psi}{\partial y_{M}}
\]

(3)

\[
W_{z} = \left( -\frac{1}{r_{M}} \right) \frac{\partial \psi}{\partial r_{M}}
\]

(4)

where \( \left[ W_{x}, W_{y}, W_{z} \right] \) are the wind vectors of point \( M \), \( r_{M} \) the distance of \( M \) to the central axis, i.e. \( r_{M} = \sqrt{(x_{M} - x_{p})^{2} + (y_{M} - y_{p})^{2}} \).

2.2. Induced velocity at central axis

Suppose the point \( M \) is located at the central axis, then \( r_{M} = 0 \), which makes Eqs.(2)-(4) invalid. As such, a potential function is adopted to derive the induced velocity on the central axis.

The potential function of point \( M \) is\cite{15}

\[
\phi = \frac{\Gamma \Omega}{4\pi}
\]

(5)

where \( \Omega \) is the solid angle of \( M \) (see Fig.2). A solid angle is defined as the ratio of the radiate surface to the whole sphere:

\[
\Omega = \frac{\Delta S \cdot 4\pi}{4\pi R_{S}^{2}}
\]

(6)

As a spherical cap truncated from the sphere, the surface area is \( \Delta S = 2\pi R_{S} h \).
Geometrically, $\Omega = 2\pi(1-\cos \theta_i)$, as a result,

$$\phi = \frac{\Gamma}{2}(1-\cos \theta_i) = \frac{\Gamma}{2}\left[1 - \frac{z}{(R^2 + z^2)^{1/2}}\right]$$

(7)

$W_z = -\frac{\partial \phi}{\partial z}$ denotes the basic relationship between potential function and velocity. In derivation of Eq.(7), the horizontal velocity is zero, and in vertical direction,

$$W_z = \frac{\Gamma}{2R} \frac{1}{\left[1 + ((z/R)^2)^{1/2}\right]}$$

(8)

At the ring’s origin, $z = 0$, thereby $W_z(0) = \Gamma/(2R)$. As a result,

$$\Gamma = 2RW_z(0)$$

(9)

This shows that the strength can be determined by the radius and the induced velocity at vortex origin.

2.3. Induced velocity in vortex core

Because of viscosity, a real vortex ring has a core, in which, the velocity reduces to zero gradually (see Fig.3). According to Eqs.(2)-(4), the velocity would increase to infinity, which obviously, does not accord with what the real wind field ought to be.

To solve this problem, some researchers used a damping coefficient to reduce the velocity gradually to zero\cite{16}. This seems rather complicated. Coupling with the principle of Rankine vortex, this article regards the core as a cylinder with a radius of $r$. In the core, the uniform distribution of vorticity ensures the vortex filament velocity to be zero, but the fluid field outside the core still conforms to stream function.

The velocity distribution of Rankine vortex is\cite{17}

$$v = \begin{cases} \frac{\omega a}{2} & a \leq r \\ \frac{\omega a^2}{2} & a > r \end{cases}$$

(10)

where $\omega$ is the rotation velocity in vortex core, $a$ the distance to central filament. Supposing the radius of core is $r$, with the following equation satisfied, point $M$ in the core will be

$$(r_1 - R)^2 + (z_1 - z_M)^2 \leq r^2$$

(11)

The height of centre $O_M$, which is coplanar with $M$, is $z_M$. From the space analytic geometry, point $O_M$ satisfies the equation:

$$Ax + y = 0$$

$$x^2 + y^2 = R^2$$

(12)

where coefficient $A$ can be determined through the coordinates of point $M$. From Eq.(12), $O_M$’s coordinates can be found. With coordinates of $O_M$ and $M$, obtained from the spatial scaling formula, the coordinates of point $N$, which is collinear with $O_M$ and the point of $M$, and located on the edge of the core, can be acquired as follows:

$$x_N = [(1 + \lambda)x_M - xo_N]/\lambda$$

$$y_N = [(1 + \lambda)y_M - yo_N]/\lambda$$

$$z_N = [(1 + \lambda)z_M - zo_N]/\lambda$$

(13)

where $\lambda = O_M M/ M N$ is the scale. Therefore, after knowing the velocity vector of $N$, the velocity of point $M$ can be acquired with Rankine vortex principle.

2.4. Declination and superposition of vortexes

The real microburst wind field is very complicated because the downdraft is not vertical to the ground and the outburst is not axis-symmetrical. Indeed, in an area, multiple storm cores and even local updrafts may exist\cite{11}.

As the vortex ring can be declined to the ground through matrix transform, the downdraft can be declined to the ground (see Fig.1). Between the primary ring coordinate system and the ground, there exist three inclination angles along three axes, $[\phi \ \theta \ 0]^T$, for which, as rotating a ring about its origin makes no sense, the third item is nil. Out of symmetry, the tilting angles of the imaginary ring are $[-\phi \ -\theta \ 0]^T$. Transition matrices $L(\phi)$ and $L(\theta)$ are used to transform the wind field from the ring coordinate system to the ground. Similarly, there also exist $L(-\phi)$ and $L(-\theta)$. Consequently, the velocity vector of an arbitrary point of $M$ can be calculated through Eq.(14).

$$\begin{bmatrix} W_x \\ W_y \\ W_z \end{bmatrix} = L(\phi)L(\theta) \begin{bmatrix} W_{xP} \\ W_{yP} \\ W_{zP} \end{bmatrix} + L(-\phi)L(-\theta) \begin{bmatrix} W_{xI} \\ W_{yI} \\ W_{zI} \end{bmatrix}$$

(14)
A real wind field with multiple cores can be formed through multi-ring superposition. By way of linear summation of multiple vortex rings with different parameters, the spatial velocity vector at a given point in the wind field is the sum of the velocity vectors induced by each of them.

3. Large Aircraft Dynamics Modeling with Wind Shear Effects

Assume that the earth is an inertial frame without consideration of its curvature and rotation. A system of aircraft general equations will be established through an Anglo-American coordinate system with a symmetric Oxy-plane.

3.1. Dynamics equations in wind-free situation

For flight simulation, the dynamics-based force and moment equations coupled with kinematic and navigation equations are used. As a part of classical content in flight dynamics, they are merely quoted and listed here\[13\].

It can be found there is a triangular relationship among ground speed \(V_E\), airspeed \(V\) and wind speed \(W\):

\[
V_E = V + W
\]  

(15)

In wind-free situation, \(V_E = V\), the force equations in body coordinate system are

\[
\begin{align*}
\dot{V}_x &= \dot{V}_xb = \frac{X}{m} - g \sin \theta - (q_{By} V_{yb} - r_{By} V_{yb}) \\
\dot{V}_y &= \dot{V}_yb = \frac{Y}{m} + g \cos \theta - (r_{By} V_{yb} - p_{By} V_{yb}) \\
\dot{V}_z &= \dot{V}_zb = \frac{Z}{m} + g \cos \theta - (p_{By} V_{yb} - q_{By} V_{yb})
\end{align*}
\]

(16)

where component forces \(X\), \(Y\), and \(Z\) constitute aerodynamic force, engine force, etc. The airspeed \(V = \sqrt{V_x^2 + V_y^2 + V_z^2}\). \(p\), \(q\), \(r\) are roll, pitch and yaw rotation speeds respectively with the \(\phi\), \(\theta\), \(\psi\) Euler angles relevant to them. Subscripts B and E indicate body frame and Earth frame respectively. In some works, force equations are made up of \(V\), angle of attack \(\alpha\) and angle of sideslip \(\beta\), in which, \(\alpha\) and \(\beta\) can be calculated as follows:

\[
\begin{align*}
\alpha &= \arctan \left( \frac{V_y}{V_x} \right) \\
\beta &= \arcsin \left( \frac{V_z}{V} \right)
\end{align*}
\]

(17)

(18)

Kinematic equations are

\[
\begin{align*}
\phi &= p_{By} + \tan \theta (q_{By} \sin \phi + r_{By} \cos \phi) \\
\theta &= q_{By} \cos \phi - r_{By} \sin \phi \\
\psi &= (q_{By} \sin \phi + r_{By} \cos \phi) / \cos \theta
\end{align*}
\]

(19)

Moment equations in body frame are

\[
\begin{align*}
\Gamma \dot{p}_{By} &= I_x (I_y - I_z) p_{By} - I_z (I_y - I_z) p_{By} + [I_x (I_y - I_z) + I_z (I_y - I_z)] + I_x \dot{L}_x + I_z \dot{L}_z \\
\Gamma \dot{q}_{By} &= (I_z - I_x) p_{By} + I_x (I_y - I_z) (p_{By}^2 - r_{By}^2) + m \\
\Gamma \dot{r}_{By} &= [(I_x - I_y) I_z + I_y (I_z - I_y)] p_{By} - I_z (I_x - I_y) \dot{L}_y + I_y \dot{L}_y \\
q_{By} \dot{p}_{By} &= I_z L_z + L_z n \\
q_{By} \dot{q}_{By} &= (I_x - I_z) L_x + L_x n \\
q_{By} \dot{r}_{By} &= (I_y - I_x) L_y + L_y n
\end{align*}
\]

(20)

where \(\Gamma = I_d I_e - I_e^2\), \(l\), \(m\) and \(n\) are composite moments.

Navigation equations are

\[
\begin{align*}
\dot{x}_E &= x_E = V_x \cos \theta \cos \psi + V_y (-\cos \phi \sin \psi + \sin \phi \sin \theta \sin \psi + V_z \sin \phi \sin \theta) + V_z \cos \phi \cos \theta \\
\dot{y}_E &= y_E = V_x \cos \theta \sin \psi + V_y (\cos \phi \cos \psi + \sin \phi \sin \theta \sin \psi) + V_z (-\sin \phi \cos \theta + \cos \phi \sin \theta) \\
\dot{z}_E &= z_E = V_x \sin \theta - V_y \sin \phi \cos \theta - V_z \cos \phi \cos \theta
\end{align*}
\]

(21)

The core dynamic equations, Eqs.(16)-(21), can be solved with real-time digital integration algorithm in simulation. For other symbols refer to Ref.[18].

3.2. Dynamics equations with wind shear parameters

If there is wind shear, then \(V_E \neq V\). By inserting Eq.(15) and its derivative into Eq.(16) and Eq.(21), the force equations with wind shear effects considered in body frame become:

\[
\begin{align*}
\dot{V}_x &= \frac{X}{m} - W_{xb} - g \sin \theta - [q_{By} (V_x + W_{xb}) - r_{By} (V_y + W_{yb})] \\
\dot{V}_y &= \frac{Y}{m} - W_{yb} + g \cos \theta - [r_{By} (V_x + W_{xb}) - p_{By} (V_y + W_{yb})] \\
\dot{V}_z &= \frac{Z}{m} - W_{zb} + g \cos \phi \cos \theta - [p_{By} (V_y + W_{yb}) - q_{By} (V_z + W_{zb})]
\end{align*}
\]

(22)

Navigation equations with wind shear effects considered in body frame become:

\[
\begin{align*}
\dot{x}_E &= x_E = V_x \cos \theta \cos \psi + V_y (-\cos \phi \sin \psi + \sin \phi \sin \theta \sin \psi + W_{xe}) + V_z \sin \phi \sin \theta \\
\dot{y}_E &= y_E = V_x \cos \theta \sin \psi + V_y (\cos \phi \cos \psi + \sin \phi \sin \theta \sin \psi + W_{ye}) + V_z (-\sin \phi \cos \theta + \cos \phi \sin \theta) + W_{ze} \\
\dot{z}_E &= z_E = V_x \sin \theta - V_y \sin \phi \cos \theta - V_z \cos \phi \cos \theta + W_{ze}
\end{align*}
\]

(23)

Since inertial force and moment are determined by ground speed, Eqs.(19)-(20) do not include wind shear parameters.

In Section 2, \([W_E, W_E, W_E]^T\) is calculated in ground coordinate system, namely, \([W_{xe}, W_{ye}, W_{ze}]^T\). Therefore, Eq.(23) can be solved directly. As for Eq.(22),
wind vector in ground coordinate system should be transformed into body frame with
\[
[W_{db} \; W_{yb} \; W_{zb}]^T = L_{BE}[W_{xb} \; W_{yb} \; W_{zb}]^T
\]
where \(L_{BE}\) is a transition matrix.

After derivation of Eq.(24), the following can be obtained
\[
[W_{db} \; W_{yb} \; W_{zb}] = L_{BE} [W_{xb} \; W_{yb} \; W_{zb}]
\]
(25)

By inserting Eq.(25) into Eq.(22), the force equations with wind shear parameters can be solved.

In real-time flight simulation, microburst model can be constructed in advance. Once acquiring the coordinates of aircraft in earth frame at sampling points, the microburst model can be used to find \([W_{xb} \; W_{yb} \; W_{zb}]\), which, after transformed by means of Eq.(24), can be inserted into all the differential equations to find solutions.

The model based on assuming mass as a point need not derivate with respect to wind shear vectors, so the simplified equations are in no position to describe large aircraft’s responses to turbulent wind. A 3D turbulent wind model thus should be built up to find accurate parameters to be inserted into the dynamic equations for further research.

3.3. Modification of aerodynamic model with wind shear effects

Turbulent wind inevitably has influences on aerodynamic forces and moments. Based on Boeing 747’s modeling data, this article does research on the wind shear effects on aerodynamics. Furthermore, a general method to modify aerodynamic model under wind shear is proposed.

The transporters of Boeing 747 series are of classical giant aircraft. Models for simulating behavior of aerodynamics, engines, control systems, etc. have already been built up with abundant experimental data in store[19-20].

According to the requirements for modeling by a flight simulator[3], aerodynamic forces and moments can be found by calculating six coefficients in real-time flight simulation. Each of them is made up of several aerodynamic derivatives, each having intrinsic mechanics meanings. Data tables have been compiled on the basis of the flight test curves and stored in real-time database. In real-time simulation, by means of multi-dimensional interpolation algorithm, the aerodynamic model can be constructed based on these data.

Essentially, wind shear effects on aerodynamics are tantamount to those on some derivatives. Two kinds of derivatives need to be modified.

The first is the derivatives \(\dot{\alpha}\) and \(\dot{\beta}\). By deriving Eq.(17) and Eq.(18), the following can be obtained:

\[
\ddot{\alpha} = \frac{V_x \dot{V}_z - V_z \dot{V}_x}{V_x^2 + V_z^2}
\]
(26)
\[
\ddot{\beta} = \frac{V_y \dot{V}_z - V_z \dot{V}_y}{\sqrt{V_x^2 + V_z^2}}
\]
(27)

After acquiring \(\dot{V}_x, \dot{V}_y, \) and \(\dot{V}_z\) with wind shear effects considered through Eq.(22), \(\dot{\alpha}\) and \(\dot{\beta}\) can be modified with Eqs.(26)-(27). In this way, the relative derivatives can be modified.

The second is the derivatives of rotation. The wind gradient effects across fuselage and wingspan can in no way be omitted when dealing with large aircraft. Wind gradients must be considered when implementing derivation with respect to angular velocity. In this respect, mass-point-assumed model is much simple for large aircraft due to its neglecting wind gradients.

Etkin presented four-point model to assess wind shear effects on aircraft rotation. By simplifying an aircraft into a 2D plane, the wind vectors on four typical points are considered. Wind gradients are calculated on the assumption of linear distribution. For a huge commonly-configured aircraft, the four points are taken in the following manner[21]: point \(O\) is located at the center of mass; points \(A\) and \(B\) which are collinear with point \(O\) at the mid are located at 85% of wingspan in opposite directions; point \(C\) which is collinear with point \(O\) is located at 25% of chord on the horizontal stabilizer (see Fig.4).

![Fig.4 Four assumed points.](image)

On the assumption of 2D planar body and linear wind shear gradient, an aircraft is subjected to the actions from four gradients, as shown in Fig.5.

Fig.5(a) shows the \(W_z\) gradient distribution across wingspan affecting roll motion; Fig.5(b) the \(W_z\) gradient distribution across fuselage affecting pitch motion; Fig.5(c) the \(W_y\) gradient distribution across fuselage affecting yaw motion, and Fig.5(d) the \(W_x\) gradient distribution across wingspan affecting roll motion. Accordingly, the angular velocities relative to turbulent wind can be expressed by

\[
\dot{p}_{rel} = p_b - \frac{\partial W_z}{\partial y}
\]
(28)
\[
\dot{q}_{rel} = q_b - \frac{\partial W_z}{\partial x}
\]
(29)
In the real-time flight simulation, the aircraft’s centre of mass can be found from Eq. (23). The other three points can be obtained by simple calculation. They are:

Point A:
\[
(x_A = x_0 + b\sin \psi / 2, y_A = y_0 - b\cos \psi \cos \phi / 2, z_A = z_0 - b\sin \phi / 2)
\]

Point B:
\[
(x_B = x_0 - b\sin \psi / 2, y_B = y_0 + b\cos \psi \cos \phi / 2, z_B = z_0 + b\sin \phi / 2)
\]

Point C:
\[
(x_C = x_0 - l_c \cos \theta \cos \psi, y_C = y_0 - l_c \sin \psi \cos \phi, z_C = z_0 - l_c \sin \theta)
\]

Next, the wind vectors at four points are acquired based on the wind shear model. After getting gradients through Eqs. (28)-(30), they are transformed into body frame as follows:

\[
\begin{bmatrix}
P_{GB} \\
q_{GB} \\
r_{GB} \\
r_{2GB}
\end{bmatrix} = \mathbf{L}_G E \begin{bmatrix}
(W_{x,A} - W_{x,B}) / b' \\
(W_{x,B} - W_{x,C}) / l_c \\
(W_{y,A} - W_{y,C}) / l_c \\
(W_{z,A} - W_{z,B}) / b'
\end{bmatrix}
\]

Finally, the angular velocities relative to turbulent wind can be found

\[
\begin{align*}
\omega_{rel} &= \omega_B - \omega_{GB} \\
\phi_{rel} &= \phi_B - \phi_{GB} \\
r_{rel} &= r_B - r_{GB}
\end{align*}
\]

By inserting the above results into relevant aerodynamic derivative terms, the derivatives with wind shear effects considered can be achieved.

4. Simulation and Verification

4.1 Simulation of microburst model

In Section 2, a microburst model can be described by \([x_p, y_p, z_p, W_z(0), R, r, \phi, \theta]\). Let the microburst model be so designed that \(z_p = -610 \text{ m}\); \(r = 458 \text{ m}\); \(W_z(0) = 10 \text{ m/s}\) and \(\theta = 45^\circ\). Fig. 6 shows the simulation results on the cross-section of central axis. By Rankine vortex principle, the wind velocity gradually reduces to zero to the filament.

Fig. 7 shows the ground wind vectors that happened sometime in some areas and were recorded by JAWS\(^{(22)}\). In flight simulation, different wind shear situations can be simulated with given landing or take-off routes. For example, route \(X'Z'\) can be used to simulate flight through strong wind shear, route \(I'J'\) can be used to simulate severe lateral wind, etc. With the proposed method, a wind field as complicated as shown in Fig. 7 can be simulated by specifying different parameters for vortexes, and then superposing them as indicated in Fig. 8. The results indicate the strong extensibility and applicability for practical uses that the microburst model has based on vortex ring and Rankine vortex.

Fig. 8 Simulated wind field by multiple ring proposition.
4.2. Simulation of flight dynamic model

Now, it is required to verify the dynamic model. As the model has been trimmed in wind-free situation, comparing the trimmed flight states with ten classical flight states[23] shows a good agreement between the simulation and the test data. This proves the preliminary success of the whole dynamics, aerodynamics and engine model.

Taking approach-and-landing as an example, the “aircraft” has been trimmed at the flight state 2[23]. The “aircraft” flights northward at a $-3^\circ$ glide slop and 83 m/s. Initial altitude is 610 m. Trim results show the lateral control and state parameters are all zero. In Fig.9, dash lines are used to illustrate the uncontrolled simulation results after inserting three control axis parameters and throttle angle into the dynamic model. The “aircraft” lands at the 143.7th second with a correct flight-path trajectory and all stable parameters. In Fig.9, $\alpha$, $\beta$, $\phi$ and $\psi$ are the angles of attack, sideslip, roll, pitch and azimuth; $H$ is the altitude.

Fig.9  Uncontrolled simulation results.

5. Real-time Simulation of Escaping Wind Shear

With the microburst model and dynamic model with wind shear effects considered, this article examines two escape schemes and makes a preliminary study on the pilot-in-the-loop escape scheme in the simulator.

Assuming the coordinate system identical with that in Fig.1, the microburst takes place at 6 000 m south of runway with central axis vertical to the ground. Other parameters are set the same as in Section 4.1. Just as the Fig.9 shows, in the uncontrolled flight, the state of aircraft is subjected to acute changes when encountering the wind. In the end, the “aircraft” crashes at the 114.8th second.

(1) Simulation of longitudinal escape

According to the longitudinal escape scheme recommended by FAA[4], when wind shear is detected, the throttle should be fully pushed to keep the pitch angle $\theta_l = 15^\circ$. An elevator proportional integral derivative (PID) controller is designed as follows to meet this requirement.

$$\delta_e = K_p (\theta - \theta_l) + K_{de} (\dot{\theta} - \dot{\theta}_l) + K_{le} \int_0^t (\theta - \theta_l) \, dt$$  \hspace{1cm} (35)

where $K_p$, $K_d$ and $K_i$ indicate the control variables.

Fig.10 shows the simulation results when the controller implements the longitudinal escape control since the 80th second. No matter how severely the state changes in the wind field, the “aircraft” manages to get rid of the wind shear with safety. The results also show that if the “aircraft” starts to escape a bit late, it would inevitably crash.

Fig.10  Aircraft longitudinal escape.

(2) Simulation of lateral control

If the “aircraft” flies through a severe lateral wind shear, a lateral escape scheme should be executed. Assuming the microburst center is located 10$^\circ$ southeast to and 7 300 m off the airport and other parameters remain unchanged, a coordinate turn controller is designed as follows

$$\delta_\phi = K_{p\phi} (\phi - \phi_l) + K_{d\phi} (\dot{\phi} - \dot{\phi}_l) + K_{le} \int_0^t (\phi - \phi_l) \, dt$$  \hspace{1cm} (36)

$$\delta_\psi = K_{p\psi} (\psi - \psi_l) + K_{d\psi} (\dot{\psi} - \dot{\psi}_l) + K_{le} \int_0^t (\psi - \psi_l) \, dt$$  \hspace{1cm} (37)

Fig.11 shows the simulation results with real lines when the “aircraft” begins escaping by turning left at the 30th second, and the coordinate turn simulation results after trim with blue lines. When the “aircraft”
approaches the center of thunderstorm, the aircraft would be subjected to serious disturbances. However, it could still keep its steady state and manage to shun the wind field with safety.

![Graph](image)

Fig.11  Aircraft lateral escape.

(3) Escape by pilot’s manual control
On the basis of observation of pilot-trainees’ escape drills, it is found that with the same model, significant differences may result from their similar operations, which relies on a lot of subjective and objective factors, such as selection of parameters for the microburst model, aircraft flight state, the ability of releasing effective alarms by the alert system and pilot-trainees’ experience and otherwise.

6. Conclusions

(1) A hi-fi parameterized 3D microburst model is developed based on vortex ring and Rankine vortex principle. The model can be extended by using vortex ring declination and multi-vortex superposition. Compared to JAWS, the proposed method can produce complicated multiple wind fields. Besides, it can be used for flight training in flight simulator.

(2) Based on dynamic equations in wind-free situation, a 6-DOF dynamic model with wind shear effects considered for large aircraft can be derived. This model fits in with common wind fields. Based on modeling data, aerodynamic model can be modified to take wind effects into account, by which the requirements for flight simulation with wind shear considered can be satisfied.

(3) Once a wind shear is detected, the aircraft must try to steer clear of it. If impossible, a longitudinal or a lateral escape scheme can be implemented depending on the concrete situation. There is a high possibility that the aircraft escapes the wind field with safety as long as the control is appropriate.

It should be pointed out that it is rather difficult to precisely simulate flight through real wind fields. By means of flight dynamic model with wind effects considered in combination with flight simulator, further theoretical and practical researches are awaited in the future.

References