Study on the influence of external wind field on the terminal trajectory of projectile-parachute system

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ABSTRACT – REZUMAT

Study on the influence of external wind field on the terminal trajectory of projectile-parachute system

Parachutes are used for aerial projectile deceleration and trajectory control in the military field. Although the existing multi-degree-of-freedom and multi-body dynamics model has a small amount of calculation, the external wind field in this model is simplified, and the influence laws of which on the terminal trajectory are not clear. Therefore, a projectile-parachute system is regarded as the research object in this work. A Fluid-Structure Interaction (FSI) model was used to analyse this system's terminal trajectory. The cases with different wind velocity, wind directions, and initial trajectory angles were calculated. As a result, the external wind field has a great influence on the terminal trajectory of this projectile-parachute system. The difference in impact points in cases is positively correlated with the external wind velocity. At the same wind velocity, the trajectory in the upwind condition is easier to change than that in the downwind condition, and the difference in impact points is negatively correlated with the initial trajectory angle. While the external wind field has little influence on the projectile-parachute system's deceleration, the swing angle, and the trajectory angle of the canopy. This system's deceleration effect in the initial dropping process is more obvious under the upwind condition, and the deceleration effect will tend to be the same with the trajectory angle close to 90 degrees. Therefore, the influence of the external wind field on the terminal trajectory can be effectively reduced by increasing the initial trajectory angle, and the changes in canopy swing angle and trajectory angle will tend to be more stable in this situation.

Keywords: *terminal trajectory, engineered fabrics, parachute, Fluid-Structure Interaction*

Studiul influenței câmpului eolian extern asupra traiectoriei terminale a sistemului proiectil-parașută

Parașutele sunt folosite pentru decelerarea proiectilelor aeriene și controlul traiectoriei în domeniul militar. Deși modelul existent cu mai multe grade de libertate și dinamică multicorp are un volum redus de calcul, câmpul eolian extern din acest model este simplificat, iar legile de influență pe traiectoria terminală nu sunt clare. Prin urmare, un sistem proiectil-parașuta este considerat obiectul de cercetare în această lucrare. Un model de interacțiune fluid-structură (FSI) a fost utilizat pentru a analiza traiectoria terminală a acestui sistem. Au fost calculate cazurile cu diferite viteze ale vântului, direcțiile vântului și unghiurile de traiectorie inițiale. Prin urmare, câmpul eolian extern are o mare influență asupra traiectoriei terminale a acestui sistem proiectil-parașută. Diferența punctelor de impact în aceste cazuri este corelată pozitiv cu viteza vântului extern. La aceeași viteză a vântului, traiectoria contra vântului este mai ușor de schimbat decât cea în direcția vântului, iar diferența de puncte de impact este corelată negativ cu unghiul traiectoriei inițiale. Câmpul eolian extern are o influență redusă asupra decelerării sistemului proiectil-parașută, a unghiului de balansare și a unghiului traiectoriei cupolei. Efectul de decelerare al acestui sistem în procesul inițial de cădere este mai evident în condiții de contravânt, iar efectul de decelerare va tinde să fie același cu unghiul de traiectorie închis la 90 de grade. Prin urmare, influența câmpului eolian extern asupra traiectoriei terminale poate fi redusă eficient prin creșterea unghiului traiectoriei inițiale, iar modificările unghiului de balansare al cupolei și unghiului traiectoriei vor tinde să fie mai stabile în această situație.

Cuvinte-cheie: *traiectorie terminală, țesături tehnice, paraşuta, interacțiunea fluid-structură*

INTRODUCTION

The parachute has been widely used in the military field because of its small size, low cost and reliable deceleration performance. Early in World War II, the parachute replaced the tail fin of conventional projectiles. This replacement shorts the length of the projectile body and increases the number of projectiles carried by aircraft. The parachute also provides projectiles with an impact angle of more than 60°, which means a broad killing range for projectiles. In addition, parachutes can prevent aerial torpedoes and mines from being damaged or bouncing off the water. Flares with parachutes can prolong the illumination time of battlefields. With the improvement of ammunition intelligence, the parachute is also used in the air delivery of terminal sensitive projectiles, blockade and control projectiles and other projectiles for precision strikes. At present, there are two main functions of parachutes in aerial projectiles. On the one hand, parachutes are used to decelerate the projectile. The deceleration of the projectile ensures that the aircraft can drop the projectile at a low altitude with high hit precision, and provides the aircraft with enough time to escape from its projectile's killing range. On the other hand, parachutes play a role in trajectory control.

With the increasing demand for precision strikes in various countries, the requirements for trajectory control in the military field are also increasing. Consequently, the trajectory analysis of the projectile-parachute system has become the focus of intelligent ammunition design. Guglieri used the six DOF and multi-body dynamics model to simulate the trajectory of the parachute-payload system [1]. The same model was also used to obtain the trajectory characteristics of air-dropped torpedoes [2], terminal-sensitive projectiles [3], blockade and control projectiles [4]. Furthermore, this model was modified by Cao in his work, the influence of random factors on the projectile trajectory and the impact point was considered [5]. At present, the six DOF and multi-body model is commonly used in the terminal trajectory analysis of the projectile-parachute system. Although low computational cost is required, the model is greatly simplified. The projectile-parachute system is regarded as a rigid body system without the asymmetric changes of the canopy in the parachute descent stage. And the influence laws on the trajectory angle and parachute opening process cannot be obtained because the external wind field is especially simplified in this model. With the development of computer hardware and the maturity of algorithms, more and more FSI models are used in parachute analysis. The application of FSI models could obtain rich information on the structure domain and flow field, and overcome shortcomings of the existing multi-DOF and multi-body dynamics model.

However, the FSI models are commonly used in the analysis of parachute inflation because of the high computational cost. The analysis of projectile trajectory is rarely published based on these models.

This work aims at obtaining the influence laws of the external wind field on the terminal trajectory of projectile-parachute system and reducing the consumption of computing resources. In this work, an aerial projectile-parachute system is regarded as the research object, the local coordinate system is applied to control the finite flow field movement, and the terminal trajectory of this system is calculated under different conditions. The influence laws of different wind velocity and direction on the terminal trajectory under different initial trajectory angles are obtained.

MATHEMATICAL MODEL

It is difficult to build the body-fitted mesh models because the gaps between the initial folded parachute structures are too small. Besides, in the parachute inflation process, large deformations and displacements occur on the canopy in a very short time, and irregular folds also occur in the meantime. The reconstruction of body-fitted mesh will further increase the difficulty and consumption of calculation. Therefore, the structure domain and flow field domain in this work are discretized by the finite element approach. The two domains above are assembled by the intercrossing approach, and calculated based on the Arbitrary Lagrange-Euler (ALE) method. This method naturally satisfies the mass conservation. Since the heat transfer is ignored, the momentum conservation equations 1 and 2 are only solved in this work. The equation 1 and 2 are coupled with each other by the contact algorithm [6]:

$$\rho \nu_{i,t} + \rho \nu_{i,j} c_j = \sigma_{ji,j} \, \rho b_i \tag{1}$$

$$\rho \dot{\nu}_i = \sigma_{ji,j} \, \rho b_i \tag{2}$$

where ρ is the density, ν – the velocity, σ – the stress, b – the body force, and c – the fluid convection velocity with reference to the flow field domain.

In order to achieve the finite flow, the field surrounds the projectile-parachute system and moves with the system at all times (figure 1). The local coordinate system is defined and applied according to three non-collinear nodes A, B and C selected on the structural domain, which axis vectors are respectively:

$$\begin{aligned} \boldsymbol{x}' &= (\boldsymbol{x}_B - \boldsymbol{x}_A)/|\boldsymbol{x}_B - \boldsymbol{x}_A| \\ \boldsymbol{z}' &= \boldsymbol{x}' \times (\boldsymbol{x}_C - \boldsymbol{x}_A)/|\boldsymbol{x}' \times (\boldsymbol{x}_C - \boldsymbol{x}_A)| \\ \boldsymbol{y}' &= \boldsymbol{z}' \times \boldsymbol{x}' \end{aligned} \tag{3}$$

where $\boldsymbol{x}_A$, $\boldsymbol{x}_B$ and $\boldsymbol{x}_C$ represent global coordinates of three nodes respectively.

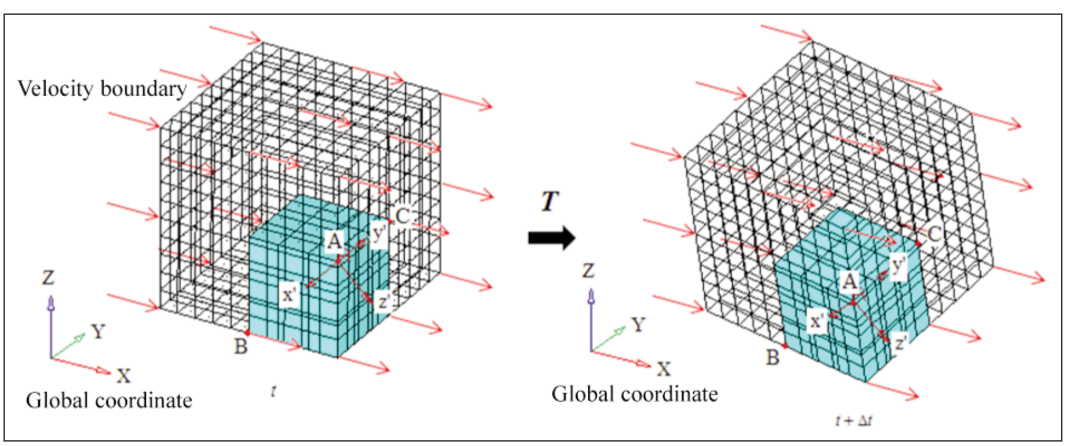


Fig. 1. Control of flow field motion

The transformation matrix $\boldsymbol{T}$ can be obtained when the local coordinate system fixed with the structure domain is displaced [6]. And the flow field's information is updated by the following equations:

$$\begin{aligned} \boldsymbol{x}_{t_0+\Delta t} &= \boldsymbol{x}_{t_0} \cdot \boldsymbol{T} \\ \hat{\boldsymbol{v}} &= (\boldsymbol{x}_{t_0+\Delta t} - \boldsymbol{x}_{t_0}) / \Delta t \\ \boldsymbol{c} &= \boldsymbol{v} - \hat{\boldsymbol{v}} \end{aligned} \quad (4)$$

where $\boldsymbol{x}$ is the node coordinates in the flow field, $\hat{\boldsymbol{v}}$ – the flow field's velocity, $\boldsymbol{c}$ – the convection velocity required by equation 1.
While the flow field is moved in the global coordinate system, the fluid material in the flow field cannot bear the shear stress, resulting in serious element distortion. Therefore, it is necessary to reconstruct the flow field grid and update the flow field information [7].

CASE STUDY

An aerial projectile-parachute system is regarded as the research object in this paper. The parachute arm length in this system is 1.8 m, and the width is 0.4 m, and the total area is 1.28 m^2, the fabric elastic modulus is 0.42 GPa, the thickness is 4 E-4 m and the fabric porosity is 0.327 m/s under 49 Pa pressure difference (in Russian standard). Moreover, the canopy in this parachute is restrained by 12 lines with a length of 1.2 m, and reinforced by crisscross reinforcements. Then the grid model shown in figure 2 is established according to the geometric characteristics of this parachute. In this model, 8,156 triangular elements are used to discretize the canopy, while 681,060 hexahedrons are used to discretize the flow field. The canopy is assembled with the flow field by the intercrossing approach.

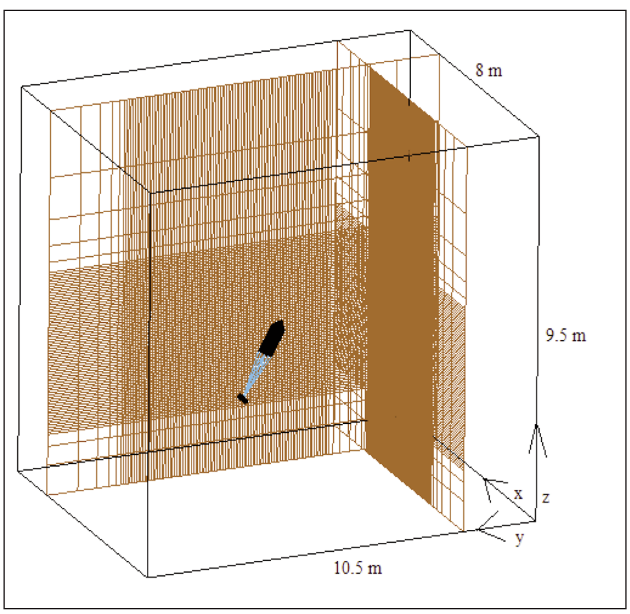


Fig. 2. The grid model

With the purpose of studying the influence laws of different wind velocity and direction on the terminal trajectory of projectile-parachute system, the different conditions shown in table 1 are calculated. The payload in all cases is 7.5 kg, the initial velocity is 300 m/s and the flight time of the projectile is 3.5 s. At the initial angle of 90°, the calculation results are the same no matter the wind field direction along with the positive or the negative X/Y axis. Therefore, the cases with the initial angle of 90° are calculated only on the condition that the wind field direction is along the positive Y axis.

Table 1

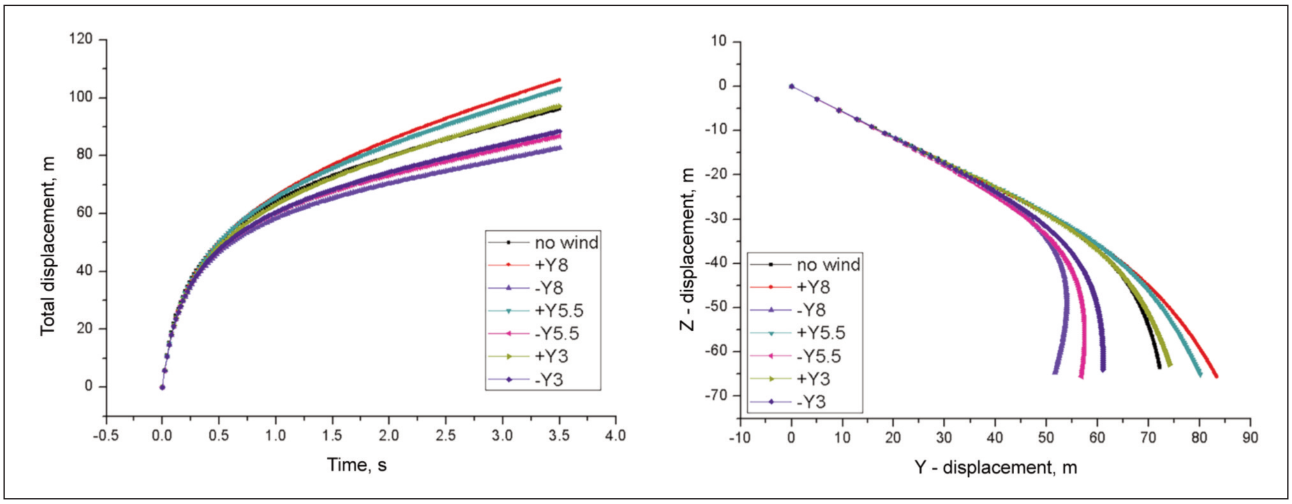
CONDITION IN CASES				
Group	**Case**	**Initial trajectory angle (degree)**	**Wind direction***	**Wind velocity (m/s)**
Group 1	Case 11	30	—	—
	Case 12		+Y	8
	Case 13		–Y	8
	Case 14		+Y	5.5
	Case 15		–Y	5.5
	Case 16		+Y	3
	Case 17		–Y	3
Group 2	Case 21	60	—	—
	Case 22		+Y	8
	Case 23		–Y	8
	Case 24		+Y	5.5
	Case 25		–Y	5.5
	Case 26		+Y	3
	Case 27		–Y	3
Group 3	Case 31	90	—	—
	Case 32		+Y	8
	Case 33		+Y	5.5
	Case 34		+Y	3

Note: +Y represents the downwind condition, –Y represents the upwind condition.

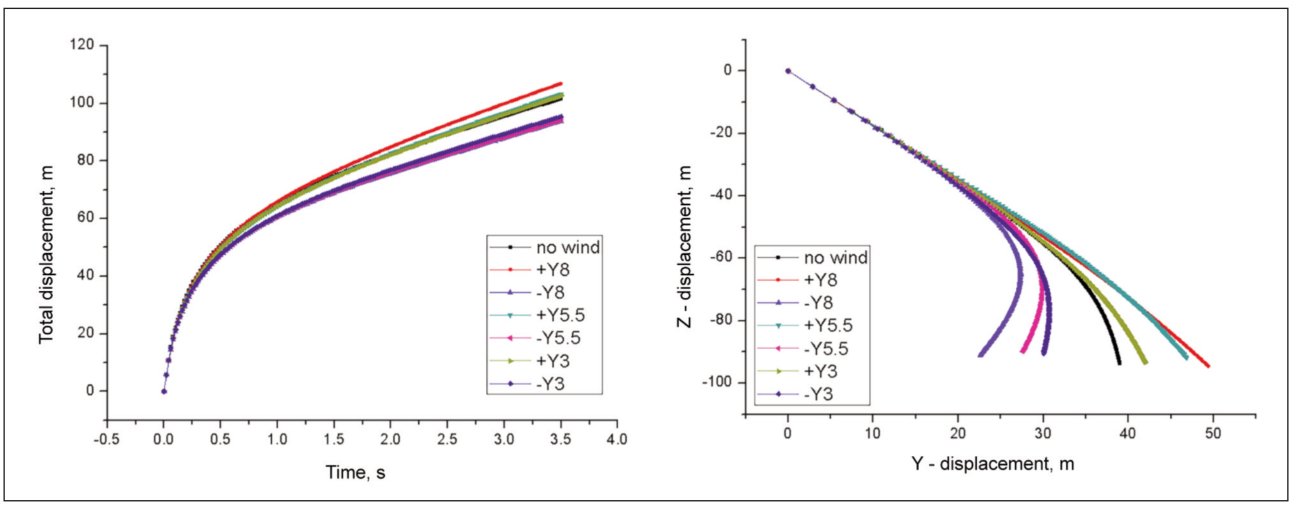
RESULTS AND DISCUSSIONS

Figure 3 shows the comparison of the total displacements and the trajectories of the projectile-parachute system in different conditions. From the comparison of total displacements, the difference between total displacements is small at the initial stage, but the difference is gradually obvious as time advance. However, the impact of external wind velocity and direction on total displacement can be enlarged by a small initial trajectory angle. When the initial trajectory angle is 30°, the maximum difference of total displacements can reach 23.3 m at 3.5 s (Case 12 and Case 13). When the initial trajectory angle is 60°, the maximum difference is 12.9 m (Case 22 and Case 23). When the initial trajectory angle is 90°, the maximum difference becomes no more than 2 m (Case 31 and Case 32). In addition, the projectile-parachute system in the upwind condition is equivalent to an additional lift applied, which causes a total displacement reduction. The reduction is increased as the initial trajectory angle increases. While the results in downwind condition are just opposite to that in upwind.

From the comparison of different trajectories, it can be found that the initial trajectory angle, wind velocity and direction have more obvious effects on the terminal trajectory. When the initial trajectory angle is 30°, and the wind velocity is 8 m/s, the maximum horizontal difference of trajectories under the downwind condition and the upwind condition is 31.7 m (Case 12 and Case 13). While the wind velocity is decreased to 5.5 m/s or 3 m/s, the maximum horizontal difference is 23.24 m (Case 14 and Case 15) and 13.06 m (Case 16 and Case 17). At the same wind velocity, the horizontal displacement difference



a



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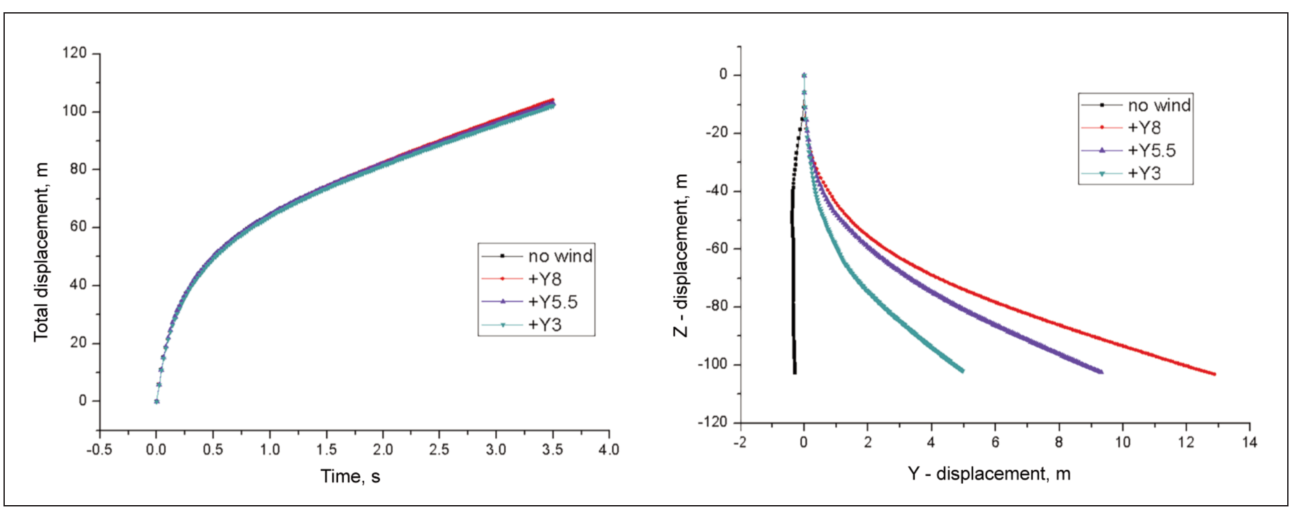
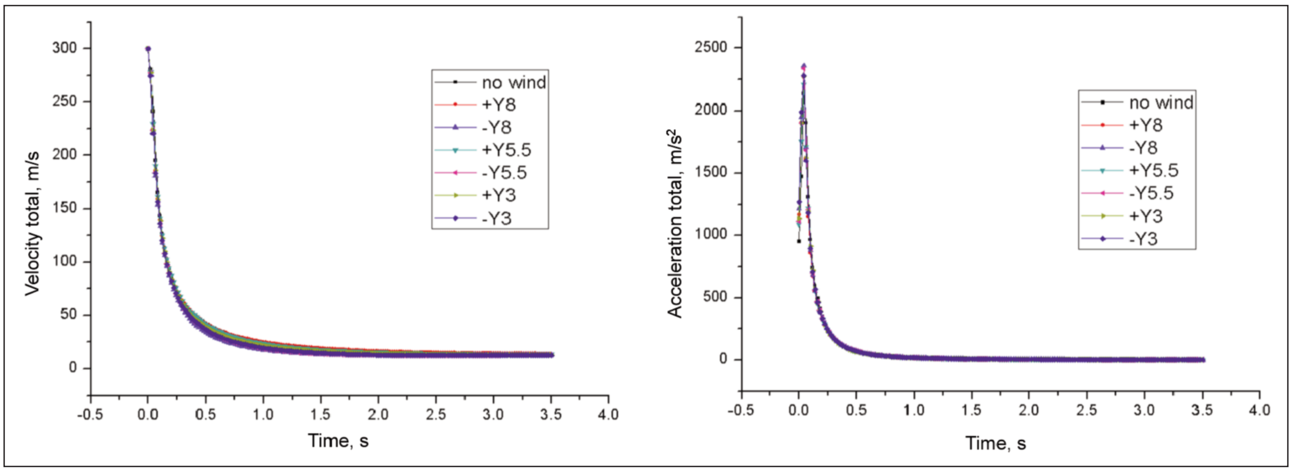


c

Fig. 3. Comparison of total displacements and trajectories: *a* – Group 1; *b* – Group 2; *c* – Group 3

is incessantly decreased with the increase of the initial trajectory angle and the decrease of the wind velocity. In addition, the trajectory of the projectile-parachute system in the upwind condition is easier to change than that in the downwind. In conclusion, the horizontal difference is negatively correlated with the initial trajectory angle and positively correlated with wind velocity.

Figure 4 shows the comparison of velocities and accelerations of the projectile. Because the parachute parameters have not changed, the characteristics of the velocity and acceleration under different conditions are almost the same. Similarly, the parachute inflation time is less affected by different conditions. The canopy in almost all cases is fully inflated within 0.04 s, and the overloads reach their maximum with a small difference in the meantime. Furthermore, the upwind condition is equivalent to an additional lift applied for the projectile-parachute system, which makes the system's deceleration effect noticeable. Therefore, the velocity of the projectile in the upwind condition is smaller than that in other



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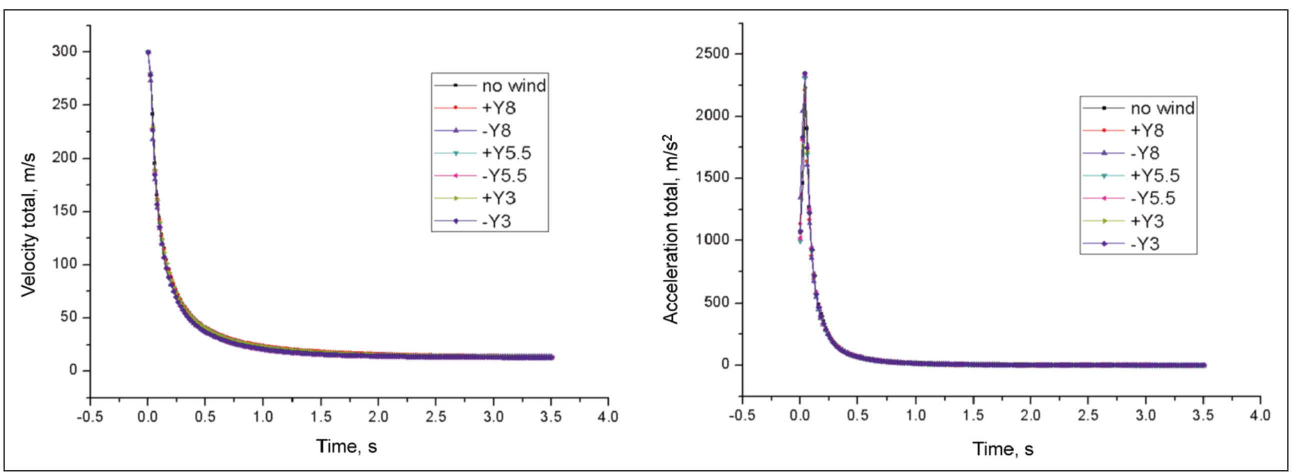

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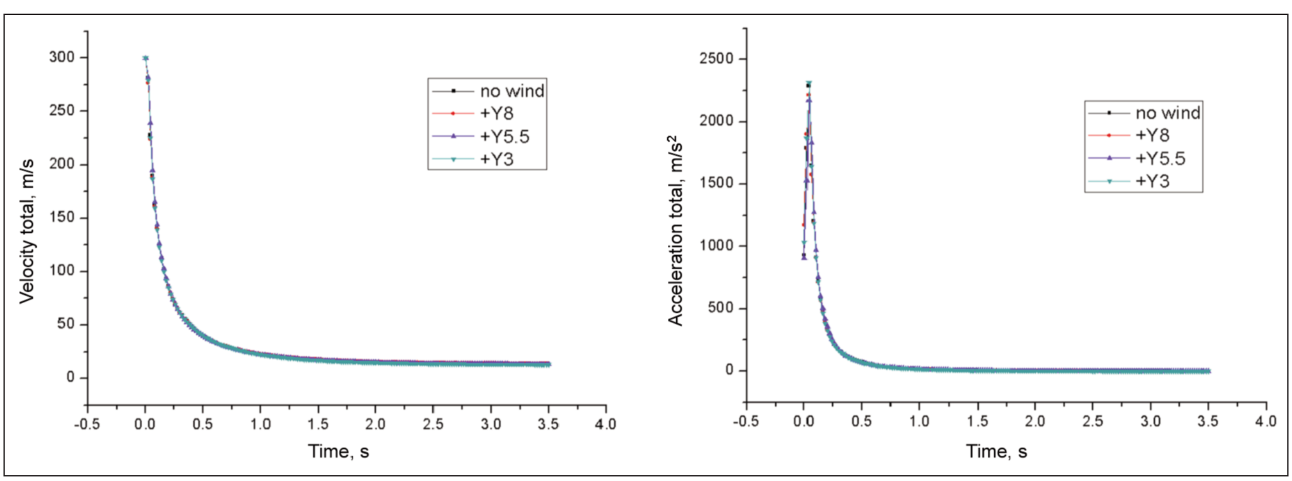

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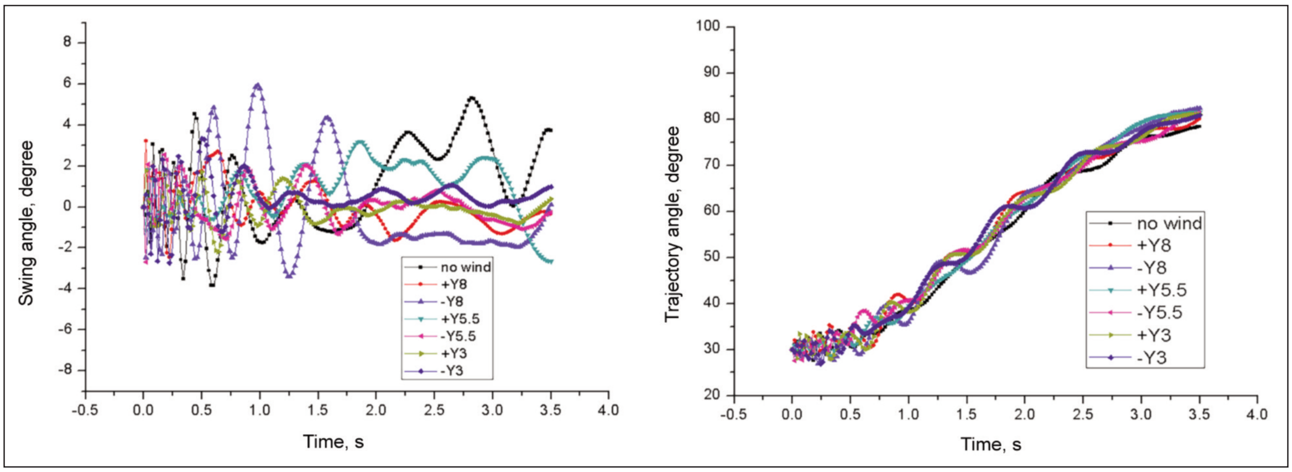
Fig. 4. Comparison of velocities and accelerations: *a* – Group 1; *b* – Group 2; *c* – Group 3

conditions at the same time. And the velocity difference caused by different conditions is decreased with the increase of the initial trajectory angle and the decrease of wind velocity. While the change of velocity difference in downwind conditions is just the reverse. The velocity difference in downwind conditions decreased with time, decreasing to 12.58–14.01 m/s at last.

Figure 5 shows the comparison of trajectory angles and swing angles of the canopy under different conditions. It can be found that the trajectory angle changes dramatically in the initial dropping stage, but as the deceleration effect becomes obvious, the change of the trajectory angle is weakened, and the trajectory angle gradually approaches 90°. The swing angle changes in a similar way. It also changes dramatically in the initial dropping stage. But the change of swing angle's frequency is decreased with the stability of the projectile-parachute system improved, and the swing amplitude is controlled within 3° (figure 5, *b* and *c*). However, there is one particular case in Group 1. The amplitude of swing angle, in this



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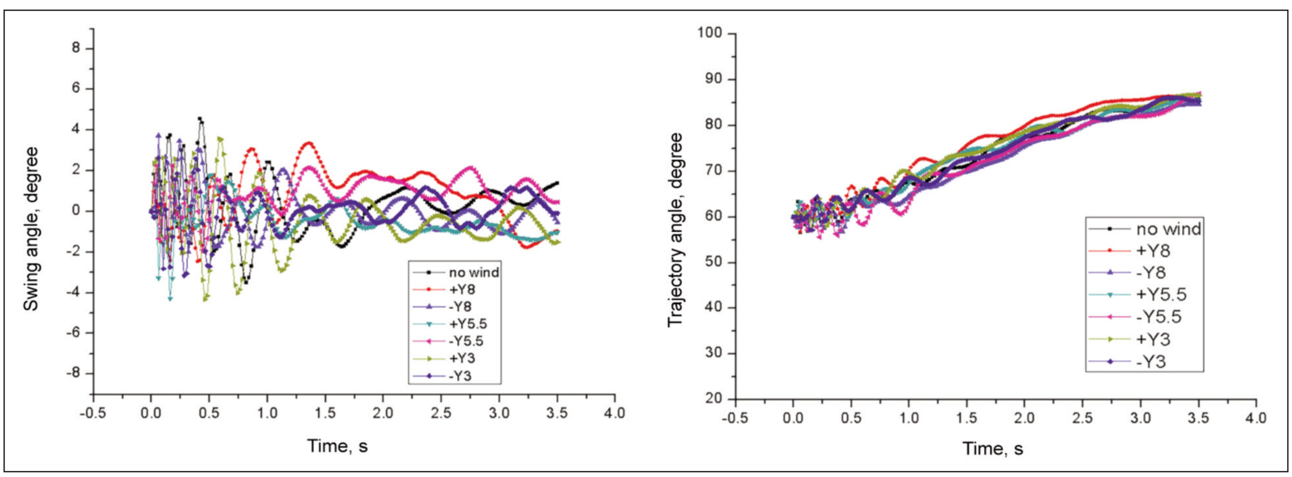

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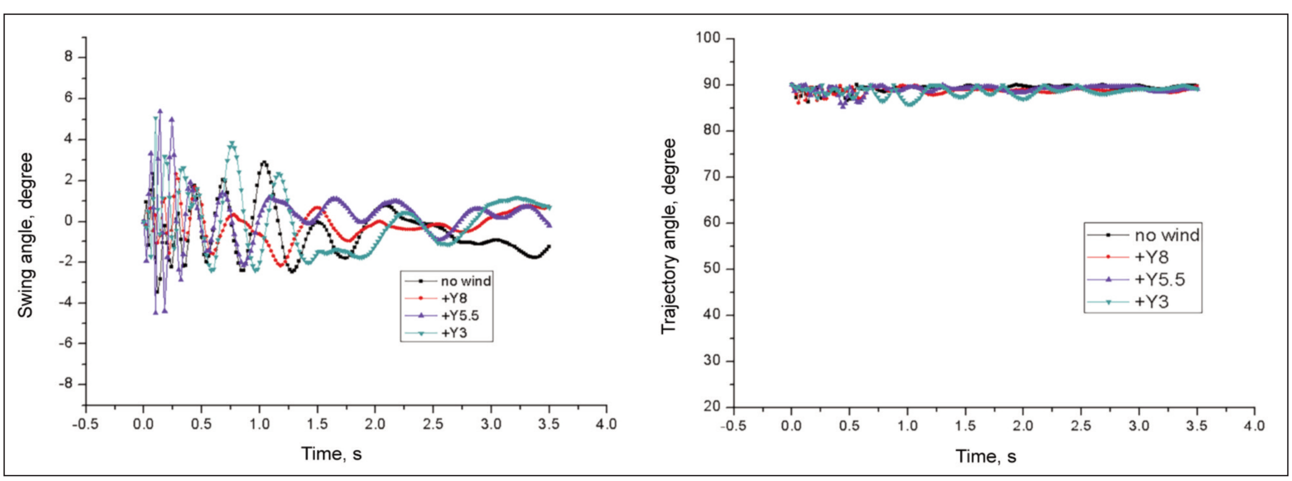

c

Fig. 5. Comparison of swing angles and trajectory angles: *a* – Group 1; *b* – Group 2; *c* – Group 3

case, is controlled within 5° at the parachute terminal descent stage. Although the parachute descent velocity is nearly constant in this particular case, the trajectory angle can't be completely stable within 3.5 s because of the small initial trajectory angle, causing larger swing angle amplitude than in other cases. In general, the swing angle and the trajectory angle of the parachute are less affected by the external wind velocity and direction. But a small initial trajectory angle can prolong the time that the swing angle and trajectory angle to be stable.

CONCLUSIONS

In order to study the influence laws of different wind fields on the projectile-parachute system's terminal trajectory, the FSI methods are used to study the influence laws of projectile-parachute system under different wind velocity, wind direction and initial trajectory angle. The following conclusions are obtained:

- The external wind field has a great influence on the terminal trajectory of the projectile-parachute system, and the impact point difference (horizontal displacement difference) is positively correlated with wind velocity. At the same wind velocity, the trajectory of the projectile-parachute system in the upwind condition is easier to change than that in the downwind condition.
- The impact point difference is negatively correlated with the initial trajectory angle. Therefore, the influence of the external wind field on terminal trajectory can be decreased by increasing the initial trajectory angle.
- The deceleration of the projectile-parachute system is less affected by the external wind field. But the upwind condition for the projectile-parachute system is equivalent to an additional lift, which enlarges the deceleration effect at the initial dropping stage. While the deceleration effect tends to be the same with the trajectory angle closed to 90°.
- The changes in swing angle and trajectory angle are also less affected by the external wind field. But a small initial trajectory angle can prolong the time of swing angle and trajectory angle to be stable.

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