Mechanical characteristics of rice seedlings under wind stress

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Abstract: Machine transplanting, as an advanced production technology, is widely used for rice cultivation. However, the transplanted rice seedlings may float over and die under the stress of external force in extreme windy weather. In order to reveal the mechanism of floating rice seedlings, it is vital to investigate their force characteristics. In this study, steady-state simulations of the flow around the rice seedlings are conducted. It is found that the drag force of rice seedlings is generated by the positive pressure of the windward side and the negative pressure of the leeward side. Both the drag force and the moment are proportional to the square of wind speed, regardless of the wind direction angle or the inclined angle of rice seedlings. The drag force coefficient exhibits a complex pattern with the wind direction angle, but decreases as the inclined angle increases. The moment arm of the drag force initially increases and then decreases with increasing wind direction angles, while it decreases with larger inclined angles. It indicates that the variation in wind direction angle may increase the risk of lodging in rice seedlings, whereas the inclined angle does not have such an effect. The results of this study provide a valuable reference for preventing the floating of rice seedlings.

Keywords: floating rice seedlings, wind stress, drag force, computational fluid dynamics
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1 Introduction

Rice, as an important grain crop, occupies a vital position in world agricultural production[1,2]. This is particularly true in Asia, where rice is not only a staple food but also a cornerstone of the agricultural economy. With the rapid development of agricultural technology, rice production methods have been significantly modernized[3-6]. Machine transplanting can substantially enhance labor productivity while reducing both labor costs and intensity[7-10]. However, in extreme windy conditions, external forces from wind and water waves can prevent the roots of transplanted seedlings from anchoring firmly in the soil. These seedlings may then float to the water surface, failing to grow normally and eventually die[11]. This phenomenon is called floating rice seedlings. It is a challenging problem that needs a traditional manual method to deal with, which is not only time-consuming and labor-intensive but also costly.

The factors influencing rice seedling floating mainly include transplanting equipment and external force stress (wind and water waves). To improve the success rate of seedling transplanting, extensive efforts have been made in this area in recent years. New transplanting mechanisms and innovative transplanters have demonstrated highly satisfactory performance in a way[12-14]. However, the mechanism and influencing factors of the external force stress remain unclear. It is crucial to carry out a dynamic response analysis of rice seedlings under the external stress.

The rice transplanting period is often accompanied by windy weather, which is the main factor causing rice seedlings to float. Due to the small size of rice seedlings, it is difficult to conduct experimental measurements of the wind force acting upon them. The rapid development of computational fluid dynamics (CFD) methods has provided an effective approach to solving this issue in recent years. The CFD method has been widely used in aerospace, automobiles, and chemical engineering, and its accuracy has been well verified[15,16]. It is not constrained by experimental site limitations or equipment size, enabling the acquisition of comprehensive flow field data and visually demonstrating complex flow phenomena, which play a critical role in the study of flow mechanisms. This technology has also been gradually introduced into agricultural research in recent years. For example, Yang et al.[17] employed the CFD method to simulate tree losses in a pine tree at different wind speeds. Wang et al.[18] assessed the effect of critical wind speed induced inversion on the quinoa yield using the CFD. Hu et al.[19] analyzed the kinematic response of rice under a near-ground wind field. Ni et al.[20] studied rice lodging in farmland wind field based on a simplified rice model by the CFD. These CFD-based studies primarily focus on mature rice seedlings or other plants, while there is a lack of research on the drag characteristics of rice seedlings during the transplanting stage under strong wind conditions.

A review of the existing literature on rice seedling floating reveals the following gaps. Firstly, there is a lack of systematic knowledge about the mechanisms of rice seedling floating. Secondly, owing to the limitations of the experimental methods, the main wind stress parameters during the process of floating rice seedlings are not clear. The rapid emergence of CFD presents a new methodology for resolving this issue. Therefore, this study employs CFD to calculate the drag force and moment on rice seedlings under varying wind speeds and directions, with the aim of elucidating the

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effects of wind force on the seedlings.

2 Model and numerical method

The studied paddy fields are located in Heilongjiang province in Northeast China. At the time of transplanting, rice seedlings typically have a height of 12-20 cm with a flat and robust stem base. The mesocotyl length is less than 3 mm, the first leaf sheath height is less than 3 cm, and the distance between auricles is about 1 cm, with leaf lengths progressively increasing. The seedlings have 3 to 5 leaves that are moderately wide and thick, with the first leaf being approximately 2 cm long, the second leaf 5 cm, and the other leaves 8 cm, showing a gradient growth pattern. The stem base is flat and wide, measuring about 2-4 mm in diameter, with a short mesocotyl and no signs of excessive elongation. A total of 100 rice seedlings during transplanting were collected as samples to characterize their morphology, and a geometric model of rice was built for the following research. As shown in Figure 1, the simplified rice seedling model consists of one stem and four leaves. The design parameters of the rice seedlings are provided in Table 1. To simplify the calculation, the rice seedling is assumed to behave as a rigid body under wind load, and its deformation is ignored.

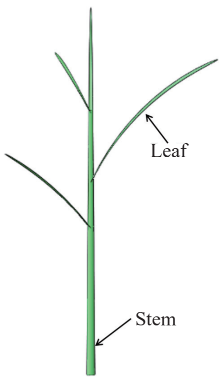


Figure 1 Model of the rice seedling

Table 1 Agronomic parameters of the rice seedlings

Parameters	Values/mm
Base stem diameter	4.0
Tip stem diameter	2.0
Leaf width	2.02-2.81
Leaf thickness	0.1
Stem height	130.0
Rice height	180.0

The computational domain is a virtual region that defines the spatial scope of numerical simulations. It directly impacts the accuracy of simulation results, computational efficiency, and physical rationality. An excessively small computational domain may cause boundary conditions to interfere with the main flow field, while an overly large domain can ensure the natural development of the flow field but significantly increases grid count and computational costs. Figure 2 shows the sketch of the computational domain of this flow. According to previous studies[16,19], to eliminate the influence of far-field boundary conditions on the calculation results, the far-field boundary should be at least 20 times the streamwise characteristic length away from the rice seedlings. The streamwise characteristic length in this study is base stem diameter D'=4 mm. Therefore, the far-field boundaries extend 25 D' (100 mm) away from the rice seedlings in the x, y, and z directions. The mesh generation is difficult duo to the size difference between the stem diameter and the leaf thickness. The area around the rice is encrypted to capture the fine flow structure. The encryption area is divided by unstructured polyhedral mesh. Following the mesh generation guidelines in references[16,19,20], the computational domain is discretized with a grid growth rate of 1.25. The minimum and maximum mesh element sizes are set to 0.04 mm and 5 mm, respectively, to ensure computational accuracy. The mesh is optimized by automatically correcting for distortion, thereby avoiding the generation of small or inverted bending units. The number of boundary layers was adjusted based on the geometry from 7 to 10. The total mesh number is about 12 million according to the above parameter settings, and the mesh of the rice is presented in Figure 3.

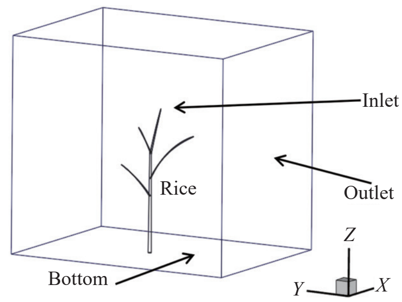


Figure 2 Sketch of the computational domain

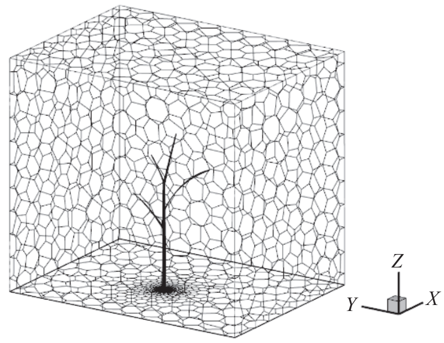


Figure 3 Grid distribution of the overall calculation domain

The fluid medium is considered continuous in fluid mechanics, and it follows the continuity equation (see Equation (1)), the momentum equation (the Navier-Stokes equation, see Equation (2)), and the energy equation (see Equation (3)). Because the flow is incompressible at low speed, the energy equation can be neglected. The steady incompressible Navier-Stokes equation and the continuity equation are solved based on the finite-volume method. The inlet boundary condition is velocity inlet, and the outlet boundary condition is pressure outlet. The adiabatic and non-slip boundary conditions are applied to the bottom boundary, and the other boundaries are symmetry boundaries. The SIMPLEC algorithm is employed to decouple pressure and velocity, and the second-order upwind scheme is adopted for spatial discretization. As the flow around rice seedlings is laminar, the laminar flow model is used in the solution process.

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \tag{1}$$

where, ρ is air density, kg/m^3; t is time, s; u_i is velocity, m/s; x_i is displacement, m; and the subscript i=1, 2, 3 implies x, y, and z directions respectively.

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where, p is pressure, Pa; τ_{ij} is viscous stress, Pa; and the subscript j=1, 2, 3 implies x, y, and z directions respectively.

$$\frac{\partial}{\partial_t}\left[\rho\left(h+\frac{1}{2}u_i^2\right)\right]+\frac{\partial}{\partial x_j}\left[\rho u_j\left(h+\frac{1}{2}u_i^2\right)\right]=\frac{\partial p}{\partial t}+\frac{\partial}{\partial x_j}\left(u_i\tau_{ij}+\lambda\frac{\partial T}{\partial x_j}\right) \quad (3)$$

where, h implies static enthalpy, J/kg; T is temperature, K; and λ is the thermal conductivity of fluids, W/m·K.

In the above equation, the deviatoric stress tensor τ_{ij} and static enthalpy h are defined as:

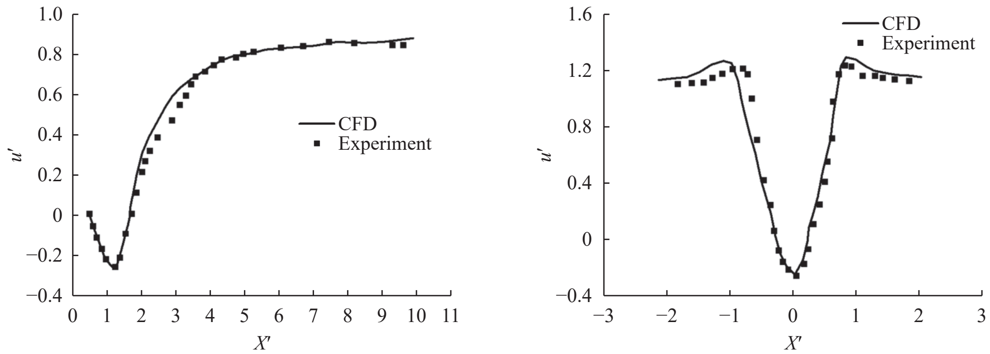
$$\tau_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\mu\frac{\partial u_l}{\partial x_l}\delta_{ij} \quad (4)$$

where, μ implies dynamic coefficient of viscosity, kg/m·s; δ_{ij} is unit tensor ($\delta_{ij}=1$ when $i=j$, and $\delta_{ij}=0$ when $i\neq j$), and the subscript l=1, 2, 3 implies x, y, and z directions respectively.

$$h=U+\int_{v_1}^{v_2}pdv=\int_{T_1}^{T_2}(c_v+R)\mathrm{d}T=\int_{T_1}^{T_2}c_p\mathrm{d}T=c_pT \quad (5)$$

where, U implies internal energy, J; v is volume, m^3; c_v is constant-volume specific heat capacity, J/kg·K; R is universal gas constant, J/mol·K; and c_p is isobaric specific heat capacity, J/kg·K.

The leaves of rice seedlings are too thin to measure force characteristics directly or indirectly through an experimental model. The flow mechanism of rice seedlings is similar to the flow around the cylinder. In order to verify the accuracy and reliability of the numerical method, the flow around the cylinder under the similar flow condition is adopted. Figure 4 compares the CFD results and the experiment data[21]. It shows that both the dimensionless mean-velocity u' of the CFD along streamwise distribution on central line and that along transverse flow direction are in agreement with the experiment, where $u'=\bar{u}/u_0$, $x'=x/D$, $\bar{u}$ is the mean-velocity, m/s; u_0 is the velocity of free flow, m/s; and D is the cylinder diameter, m. It indicates that the numerical method is reliable and can provide high-accuracy results for the subsequent analysis of rice seedlings.



a. Dimensionless mean-velocity along streamwise distribution b. Dimensionless mean-velocity along transverse direction

Figure 4 Comparison of CFD results and the experiment data

3 Results and discussions

The wind speed and direction in nature exhibit complex spatiotemporal variation characteristics, while rice seedlings demonstrate intricate dynamic response patterns in their posture under wind forces. The aerodynamic force of rice seedlings under wind stress is mainly affected by wind speed, wind direction, and their postures. Hence, combining with the meteorological data of rice-producing areas, the influence of the above factors on the aerodynamics of rice seedlings was studied.

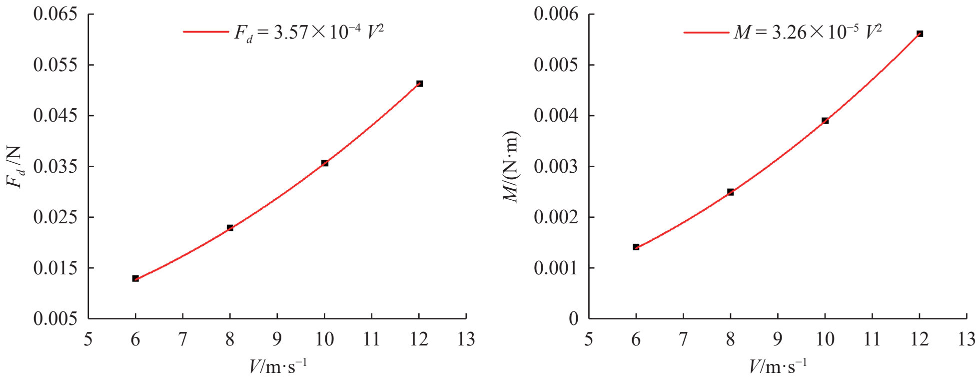
3.1 Effect of wind speed on drag force characteristics

A weather station was used to record wind speed data for the paddy fields during the rice-growing period. The rice seedling transplanting period in Heilongjiang Province primarily occurs from mid to late May. Due to the activity of cold air masses in the region, average wind speeds range from 5.0 to 14.0 m/s (Beaufort scale 4 to 6), with gusts between 8.0 and 14.0 m/s (Beaufort scale 5 to 6). Based on these data, the wind speeds of 6 m/s, 8 m/s, 10 m/s, and 12 m/s were adopted to analyze the effect of wind speed on the aerodynamics of rice seedlings.

The aerodynamic forces mainly include lift force, drag force, and its moment. The effect of lift force on the rice is neglected, because the lift force of rice seedlings is far less than their drag force in this study. The drag force refers to the resistance generated when wind acts on the surface of rice seedlings' stems and leaves, with its direction perpendicular to the flow of wind. The moment of drag force denotes the bending effect induced by the drag force acting on rice seedlings. The drag force and its bending moments are critical mechanical parameters characterizing the motion response and lodging resistance of rice seedlings under wind loading. It means that the drag force and its bending moments are the important parameters evaluating the effect of wind stress on rice seedlings lodging and floating. Therefore, only the drag force (F_d, N) and its moment (M, N·m) are presented in the later section.

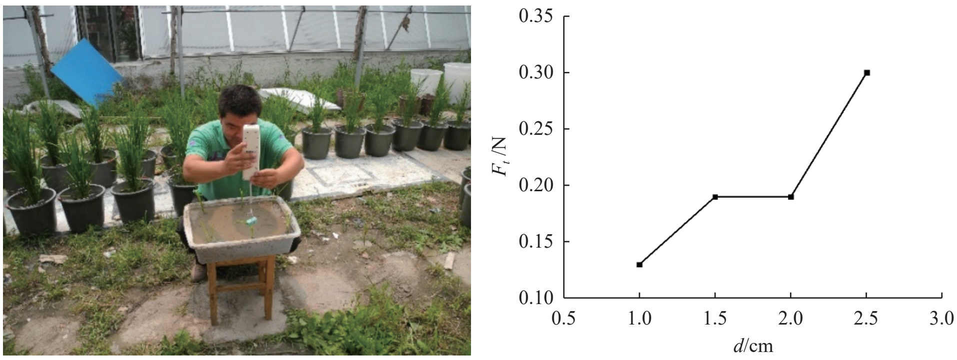
Figure 5 illustrates the drag force and its moment of the rice seedling with different wind speeds, the points represent the calculated drag forces with different wind velocities, and the red line presents the fitted curve by calculated results. It shows that both the drag force F_d and its moment M are proportional to the square of wind speed. When the wind speed reaches 12 m/s, both the drag force and the moment reach the maximum value, where the drag force is about 0.055 N, and its moment is about 0.005 N·m.

To evaluate the effect of wind force on floating rice seedlings, the soil anchorage capacity was measured, which represents the pull-out resistance provided by soil to anchoring rice seedlings. Due to the small size of individual rice seedlings, direct measurement was impractical. Therefore, a grouped testing method was adopted, in which three seedlings were treated as one experimental unit, with three replicate trials conducted. The average value of these trials was used for analysis. Both pot-grown seedlings (with root ball) and conventional bare-root seedlings were transplanted at four insertion depths (1 cm, 1.5 cm, 2 cm, and 2.5 cm) into the soil. The leaves were clamped with forceps, and a high-precision tensile testing machine was employed to measure the anchorage resistance of potted seedlings at each depth, as illustrated in Figure 6. It shows the soil anchorage capacity of rice seedlings with different soil depths[22]. It is found that the soil anchorage capacity F_t increases with the soil depth d. The drag force at the wind speed of 12 m/s accounts for 42% of the soil anchorage capacity of d=1.0 cm. These results indicate that the wind stress has a significant effect on rice seedlings. During the field transplanting process, due to variations in the evenness of paddy field soil and fluctuations in the planting depth regulated by the rice transplanter, it is challenging to maintain consistent soil depth around the root systems of individual rice seedlings. If the rice seedlings have a small soil depth, the wind force may lead to rice seedlings lodging and floating.



a. Drag force b. Moment

Figure 5 Drag force and its moment of the rice seedling at different wind speeds



a. Measuring sketch b. Soil anchorage capacity of rice seedlings

Figure 6 The measuring result of soil anchorage capacity

Referring to the paper[19], the drag force of an object can be expressed as shown in Equation (6). Based on these known parameters of air density ρ and windward area A, the drag force coefficient C_d= 0.951 can be calculated. The moment M is equal to the product of the drag force F_d and the arm of force r. It is found that all the arms of drag force at different wind speeds are equal to 9.13 cm, which illustrates that the wind speed has no effect on the moment arm of drag force.

$$F_d = \frac{1}{2}\rho V^2 C_d A \tag{6}$$

where ρ=1.225 kg/m^3 is the density of air under standard atmospheric pressure; V is wind speed, m/s; C_d is the drag force coefficient; and A is the windward area, m^2.

The results indicate that the drag force of rice seedlings with various wind speeds can be calculated by Equation (6). It has great significance for analyzing force characteristics of rice seedlings under wind stress.

To analyze the generation mechanism of the drag force, the surface pressure (gauge pressure) contours of the rice seedling at different wind speeds are presented. As illustrated in Figure 7, the windward face of rice generates positive pressure whose direction is in the same direction as the drag force. This positive pressure is generated by the deceleration of airflow upon impacting the surface,

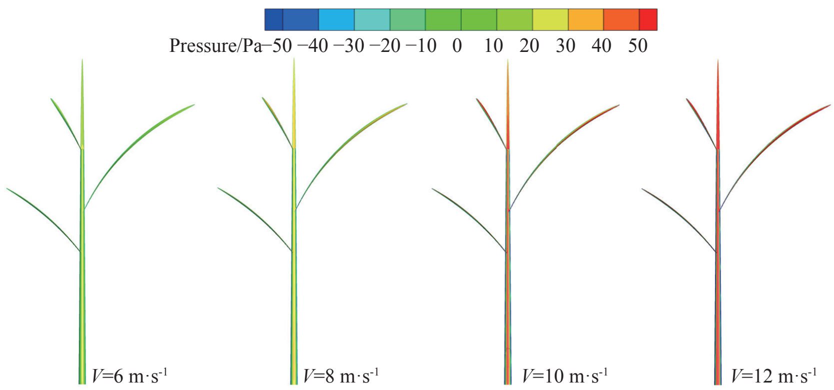


Figure 7 Pressure contour of the windward face of rice seedling at different wind speeds

and its magnitude increases with wind speed. Conversely, the leeward side of rice seedlings generates negative pressure, shown in Figure 8, which has the opposite direction to the drag force. Their resultant force forms the drag force. Both the positive pressure and the absolute value of negative pressure increase with the wind speed increasing, which explains the corresponding increase in drag force.

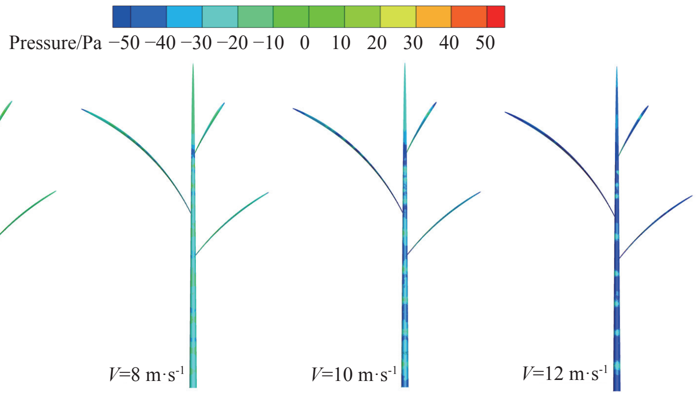


Figure 8 Pressure contour of the leeward face of rice seedling at different wind speeds

Figure 9 shows the *Z* vorticity contour of the windward face of rice seedling at different wind speeds to illustrate the generation mechanism of negative pressure. As shown in the figure, when the air flows around a rice seedling, viscous effects induce boundary layer separation, leading to the formation of vortex structures attached to the leeward side of rice seedlings. These bound vortices induce negative pressure on the leeward side of rice seedlings. The vortex strength is enhanced with the wind speed increasing, which explains the corresponding increase in the absolute value of negative pressure with the wind speed increasing.

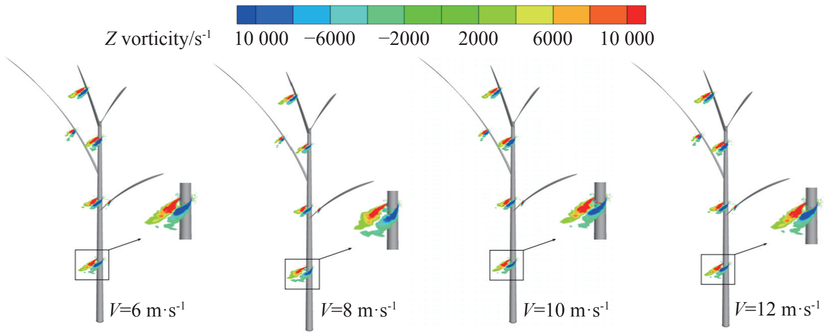


Figure 9 *Z* vorticity contour of the windward face of rice seedling at different wind speeds

3.2 Effect of wind direction on drag force characteristics

The wind direction is usually complex and variable in the natural environment. The variation in wind direction changes the windward area of rice seedlings and their surrounding flow structure, leading to variations in both the direction and magnitude of the drag force. In this study, the angle between the wind direction and the positive *x*-direction is defined as the wind direction angle α, as illustrated in Figure 10. To study the pattern of drag force coefficient and the moment arm of drag force with wind direction, four wind direction angles are selected counterclockwise starting from the forward direction.

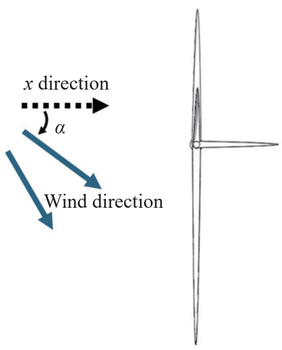
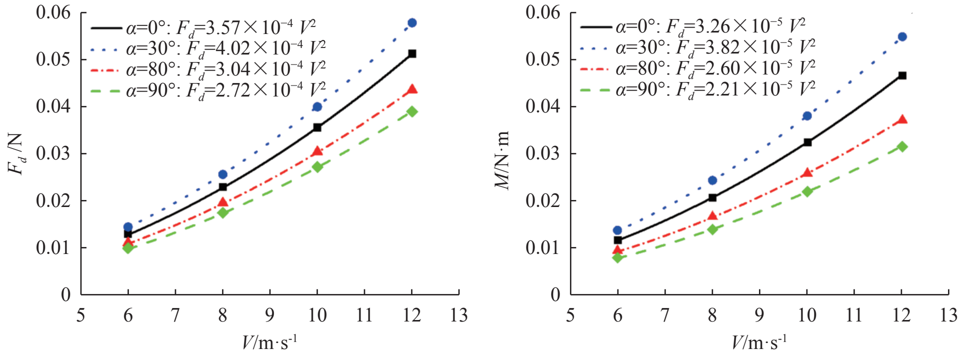


Figure 10 Sketch of wind direction angle

Figure 11 compares the drag force and its corresponding moment on the rice seedling across different wind speeds and directions. It shows that both the drag force F_d and its moment M are proportional to the square of wind speed, regardless of the wind direction. At the same wind speed, the drag force increases first and then decreases as the wind direction angle increases. The moment of drag force shows the same changing pattern. The drag force and its moment with a wind direction angle $\alpha = 30°$ have maximum values. The above results show that the characteristics of drag forces are highly dependent on the wind direction, and the variation of wind direction angle may increase the risk of rice seedlings lodging.

Figure 12 presents drag force coefficient of rice seedling versus wind direction angle to analyze the drag force characteristics in depth. It is clear from Figure 12 that the drag force coefficients of rice seedlings at different wind direction angles are variable, and it shows a complex changeable pattern as the wind direction changes. Further analysis of Figure 9 reveals that when wind direction changes, the mutual interference between vortex systems behind rice seedling leaves and stems induces variations in the pressure differential force between windward and leeward surfaces, thereby causing corresponding variations in the drag coefficient of rice seedlings. It is crucial to emphasize that these variations are distinct from mere windward area changes and rather stem from intrinsic alterations in the aerodynamic flow mechanisms. This phenomenon fundamentally underscores the strong directional dependence of drag characteristics in rice seedlings under varying wind directions.



a. Drag force b. Moment

Figure 11 Comparison of drag force and its moment of the rice seedling with different wind speeds and directions

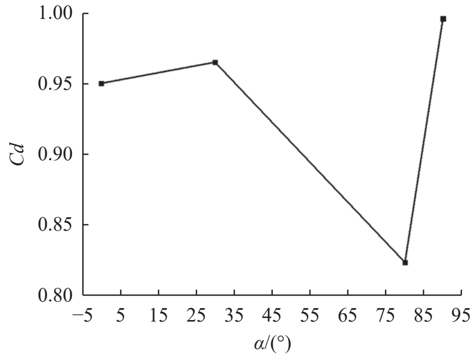


Figure 12 The drag force coefficient of rice seedling versus wind direction angle

Figure 13 illustrates the moment arm of drag force and the windward area for rice seedling versus wind direction angle. Both the moment arm of drag force and windward area of rice seedlings increase first and then decrease as the wind direction angle increases, which shows the same changing pattern as the drag force and the moment of drag force. It indicates that the moment arm of the drag force varies under different wind directions, and its variation may be related to the change of the windward area of rice seedlings. A longer moment arm is mechanically disadvantageous for rice seedlings, as it increases the bending moment for a given drag force, thereby elevating the risk of lodging.

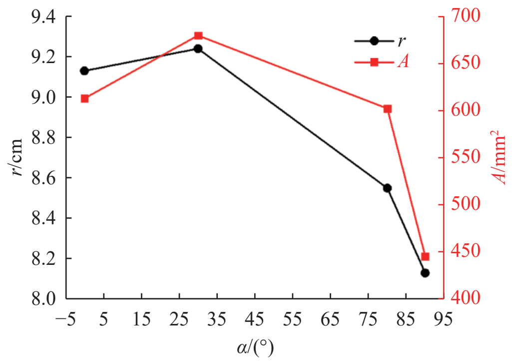


Figure 13 The moment arm of drag force and the windward area for rice seedlings versus wind direction angle

The above results demonstrate that changes in wind direction cause alterations in the flow structure around rice seedlings, which leads to variations in their drag coefficient and the moment arm of drag force of rice seedlings. These changes will have a significant impact on the mechanical properties of rice seedlings under wind stress. Consequently, this finding provides critical theoretical guidance for research on rice seedling drift (floating seedling phenomenon) and related agronomic control strategies.

3.3 Effect of rice posture on drag force characteristics

The posture of rice seedlings under wind stress continuously changes as they tilt. This alters their windward area and the surrounding flow structure, consequently changing the drag force characteristics. The angle between the wind direction and the *z*-direction is defined as the inclined angle θ, and its sketch is shown in Figure 14. The range of inclined angles is from 0° to 90°. To study the pattern of drag force coefficient and the moment arm of drag force with the posture of rice seedlings, the inclined angles at an interval of 30° in the range are selected. The rice seedlings are considered fully lodged when θ=90°, at which point there is no further research significance. Therefore, three inclined angles of 0°, 30°, and 60° are selected.

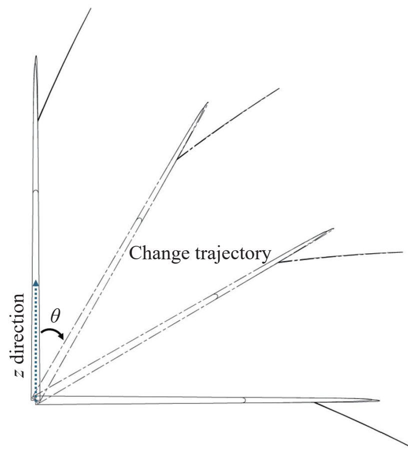


Figure 14 Sketch of inclined angle of rice seedlings

Figure 15 illustrates the comparison of drag force and its moment of the rice seedlings with different wind speeds and inclined angles. It shows that all the drag force F_d and its moment M at different inclined angles are proportional to the square of wind speed. The drag force decreases at the same wind speed as the wind inclined angle increases. The moment of drag force shows the same change pattern, but the rate of decrease is increasing. The above results show that the increase of inclined angle does not increase the risk of rice seedlings lodging. However, this process is usually accompanied by a rapid decline in the root-soil anchorage capacity of rice seedlings, so the rice seedlings can still float over.

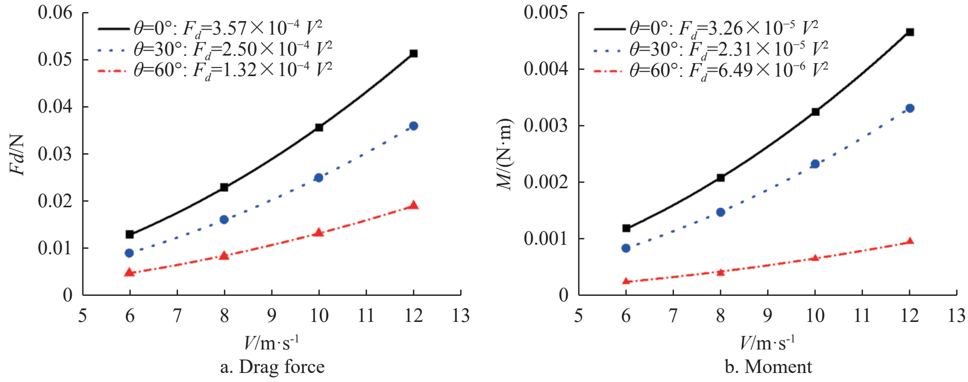


Figure 15 Comparison of drag force and its moment of the rice seedlings with different wind speed and inclined angle

Figure 16 shows the drag force coefficient of rice seedlings versus wind direction angle. It shows that the drag force coefficients of rice seedlings decrease with the increasing inclined angle, which indicates that the rice seedlings at different inclined angles have different flow mechanisms. Based on the preceding analysis (see Figures 9 and 11), it demonstrates that the inclined angle of the rice seedlings has an aerodynamic influence on drag characteristics that is comparable in magnitude to that of the wind direction angle.

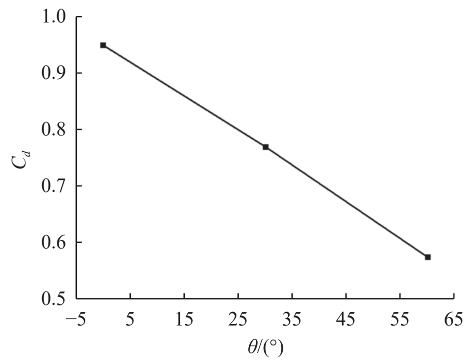


Figure 16 The drag force coefficient of rice seedling versus inclined angle

Figure 17 illustrates the moment arm of drag force and the windward area for rice seedlings versus inclined angle. The moment arm of drag force of rice seedlings increases first and then decreases as the inclined angle increases. However, the moment still shows a decreasing trend because of the substantial reduction in the drag force. Furthermore, it is not difficult to find that the windward area of rice seedlings decreases with the increasing inclined angle, which shows a different pattern from the moment arm of drag force. This suggests that the variant of windward area changes the varying pattern of the moment arm of drag force. Furthermore, the moment arm of drag force in the ideal case should decrease during the process of rice lodging. However, its actual variation pattern exhibits greater complexity, indicating that the mechanisms of wind force action during the lodging process of rice seedlings are characterized by multifaceted interactions.

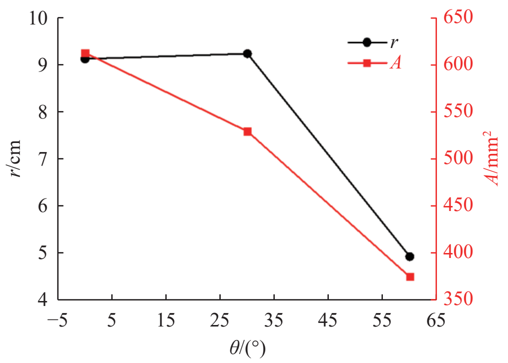


Figure 17 The moment arm of drag force and the windward area for rice seedlings versus inclined angle

The above results indicate that the variation in wind direction causes changes in the flow structure around rice seedlings, thereby affecting both the drag coefficient and the moment arm of the drag force. These changes have important implications for studying the mechanical characteristics of rice seedlings under wind stress.

4 Conclusions and future work

In this study, steady-state numerical simulations are conducted for the rice seedlings under wind stress. The changing patterns of the rice seedling's drag force and its moment with the wind speed, wind direction, and the rice posture are revealed. The following conclusions are drawn.

1) The drag force of rice seedling is generated by the positive pressure on the windward side and the negative pressure on the leeward side. The former is induced by the deceleration of airflow, and the latter is induced by vortices attaching. Both the drag force and the moment are proportional to the square of the wind speed and play a critical role during the process of rice seedling lodging.

2) Both the drag force and the moment at different inclined angles exhibit a quadratic relationship with wind speed. They increase first and then decrease at a constant wind speed as the wind direction angle increases. The moment arm of drag force shows the same change pattern. In contrast, the drag force coefficient displays a more complex relationship. These results indicate that variation of wind direction angle may increase the risk of rice seedlings lodging.

3) The drag force and its moment at different inclined angles are proportional to the square of wind speed. They decrease at the same wind speed as the wind inclined angle increases. The drag force coefficients of rice seedlings decrease as the inclined angle increases. Although there is a brief increasing process of its moment arm with increasing inclined angle, the moment still exhibits an overall decreasing trend because of the substantial reduction in the drag force. Therefore, it is concluded that the increase in the inclined angle does not elevate the lodging risk of rice seedlings.

However, the above conclusions are based on the steady-state flow assumption, and do not account for the unsteady effect of the flow around the rice seedlings and the deformation of rice seedlings under wind stress. In the future, the unsteady effect will be further studied based on unsteady numerical simulations, particularly focusing on the dynamic vortex shedding patterns and pressure fluctuation characteristics. Additionally, the fluid-structure coupling problems involving rice seedlings deformation will also be considered to clarify the dynamic response mechanisms of rice seedlings under wind stress.

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