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Trajectories of plate-type wind-borne debris considering mass eccentricity

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SUMMARY:
Wind-borne debris is the main factor that causes damage to the building envelope in wind disasters. Based on a new quasi-steady theoretical rotational force model, the influence of mass eccentricity moment is introduced and analysed. The results show that the flight trajectories of plate wind-borne debris are very sensitive to the location of mass eccentricity. In general, the impact of mass eccentricity is consistent with the larger the deviation of the centre of mass is, the more the flight trajectories offset. If the centre of mass deviates to different sides of the plate, the flight path will shift up or down in different directions. Therefore, the existence of mass eccentricity will cause the distribution range of debris flight trajectories to expand, and the possible damage is also greater, which is worthy of being used as an important parameter for the study of wind-induced debris flight trajectory and the establishment of a wind disaster model.

Keywords: plate-type wind-borne debris, mass eccentricity, flight trajectory

1. INTRODUCTION

In hurricane-prone coastal areas, wind-induced debris is the main cause of building envelope damage, and plate-type wind-induced debris is a more common form of debris. A classic study about debris was conducted by Tachikawa, who studied the aerodynamic characteristics and flight trajectories of plates with several different geometric parameters in wind tunnel, and provided the motion equations of plate debris (Tachikawa, 1983), laying a foundation for a series of subsequent studies. Since then, many scholars have studied wind-induced fragments, especially plate-type debris. Lin et al. studied the flight trajectories of plate-like fragments under strong winds through full-scale experiments, and derived empirical formulas for estimating horizontal flight speed and distance (Lin et al., 2006). Baker gave the equation of motion of the sheet fragments in a generalized dimensionless form, revealing the main control parameters of the problem (Baker, 2007). Richards et al. measured the force coefficient of plate fragments in three-dimensional state by wind tunnel experiment, and proposed a 6-degree-of-freedom trajectory model using the measured forces and pressure centre position model (Richards et al., 2008). Since then, improvements have been made to the proposed trajectory model. For example, a three-dimensional motion numerical model of plate-like fragments under a uniform wind field was proposed, which was quaternion-based (Fu et al., 2013), and a Monte Carlo simulation engine was used to account for the uncertainties generated by vertical and lateral gust wind velocity components (Huang et al., 2016). Based on previous research, Lin et al. studied the effects of geometry, Reynolds number and rotation direction on the average force coefficient of rotating plates through wind tunnel tests, and proposed a new quasi-steady theoretical rotational force model, which has better experimental trajectories matching (Lin et al., 2022).

However, in actual wind disaster scenarios, the source and generation of wind-borne debris are very complex, and the fragments are often objects with uneven mass, or the mass of the fragments is eccentric due to irregular shapes. It is obvious that the existence of mass eccentricity will affect the flight trajectories of debris. In this paper, based on the rotational force model of quasi-steady theory of plate-like fragments in uniform flow improved by Lin et al. (2022), the flight trajectories of plate debris under the influence of mass eccentric moment are studied.

2. MOTION MODEL OF PLATE-TYPE DEBRIS WITH MASS ECCENTRICITY

The force of plate fragments moving in the flow field is relatively complex. Considering the simplification of two-dimensional trajectory, the force diagram of the plate with eccentric mass is shown in Fig. 1. Where, l is the length of the plate and t is the thickness; L, D and M respectively represent the lift force, drag force and moment on the plate, mg is the gravity, and e is the distance between the center of mass and the center of shape of the plate. θ represents the angular rotation, β indicates the angle of attack of the wind relative to the horizontal direction. Uw and Vw represent the horizontal and vertical incoming wind speeds respectively, u and v represent the horizontal and vertical movement speeds of debris, and Ur represent the relative wind speeds, $Ur=[(Uw-u)^2+(Vw-v)^2]^{0.5}$.

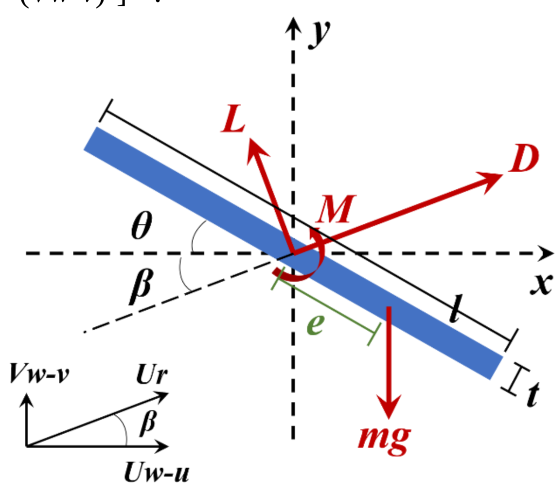


Figure 1. Schematic diagram of the force of plate windborne debris.

Referring to the study of Lin et al. (2022), the motion equations of plate windborne debris can be represented by Eq. (1)-(3):

$$\frac{d^2x}{dt^2} = \frac{A\rho U_r}{2m}[(C_{DR} + C_{DS})(U_w - u) - (C_{LR} + C_{LS})(V_w - v)] \tag{1}$$

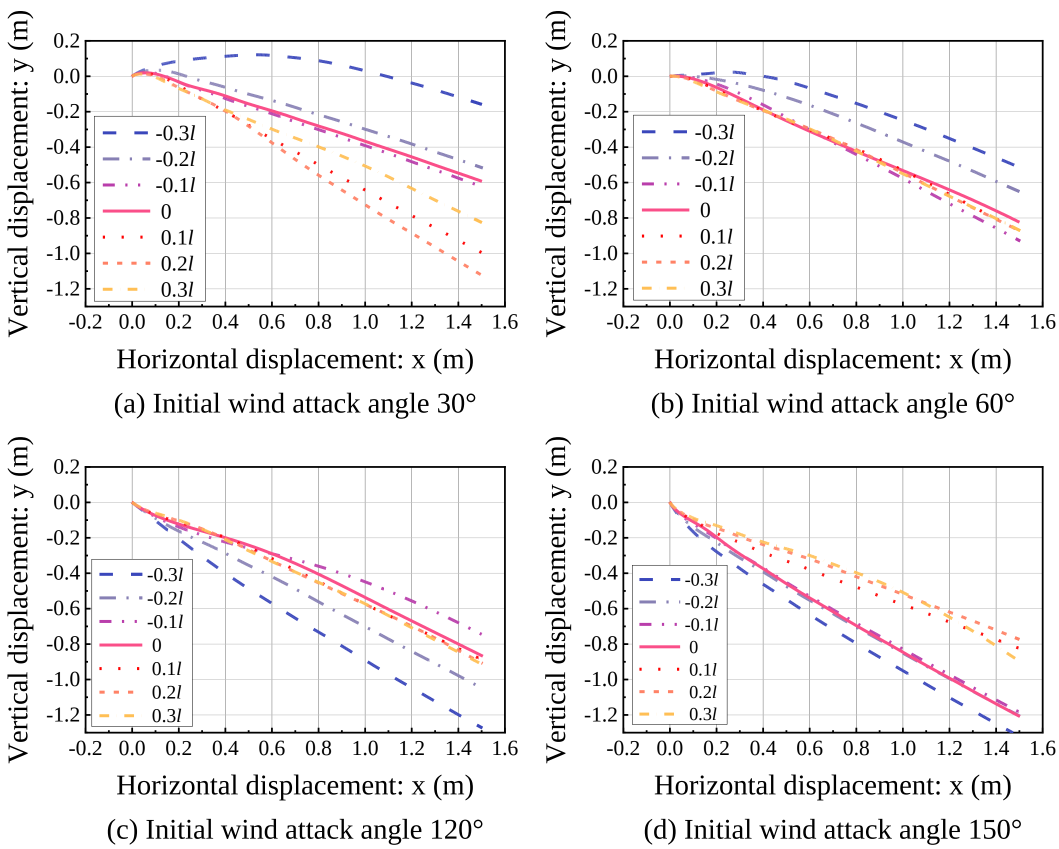
$$\frac{d^2y}{dt^2} = \frac{A\rho U_r}{2m}[(C_{DR} + C_{DS})(V_w - v) + (C_{LR} + C_{LS})(U_w - u)] - g \tag{2}$$

$$\frac{d^2\theta}{dt^2} = \frac{A\rho l U_r^2}{2I}(C_{MR} + C_{MS}) \tag{3}$$

Where, x, y and θ respectively represent the horizontal displacement, vertical displacement and angular displacement of the plate. A is the area of the plate, ρ is the air density, m is the mass of the debris, g is the acceleration of gravity, and I is the moment of inertia, $I=m\cdot(l^2+t^2)/12$. C_{LS}, C_{DS} and C_{MS} respectively represent lift, drag and moment coefficients in static state; C_{LR}, C_{DR} and C_{MR} respectively represent lift, drag and moment coefficients in rotating state; other symbols are shown as mentioned above. In this paper, the force coefficient model modified by Lin et al. (2022) is adopted for $C_{LS}+C_{LR}$, $C_{DS}+C_{DR}$ and $C_{MS}+C_{MR}$. As can be seen from Fig. 1, in addition to lift, drag and moment due to incoming flow, the moment due to mass eccentricity also needs to be considered. Although the aerodynamic forces of the debris are related to many factors, such as aspect ratio, width ratio and angle of attack, they are independent of the position of the center of mass. Therefore, the aerodynamic model of the fragment with eccentric mass is equivalent to adding an eccentric moment to the aerodynamic model of the fragment with uniform mass distribution. The eccentric moment coefficient is defined as shown in Eq. (4). In the flight trajectory simulation of mass eccentric fragments, it is only necessary to replace $C_{MS}+C_{MR}$ in Eq. (3) with C_{Mtotal} in Eq. (5).

$$C_{Me} = \frac{mg\cdot e\cdot\cos\theta}{0.5\rho U_r^2\cdot Al} \quad (4)$$

$$C_{Mtotal} = C_{MS} + C_{MR} + C_{Me} \quad (5)$$



(a) Initial wind attack angle 30° (b) Initial wind attack angle 60°
(c) Initial wind attack angle 120° (d) Initial wind attack angle 150°

Figure 2. Influence of mass eccentricity on the flight trajectories of plate windborne debris.

3. RESULTS AND DISCUSSION

Fig. 2 shows the flight trajectories of square fragments with mass eccentricity at different initial wind attack angles. Where, the wind speed (*Uw*) is 9.2 *m/s*, the mass of the square plates (*m*) is 3.584*g*, and the geometric dimensions of length, width and thickness are 40×40×2 *mm*. As can be seen from the Fig. 2, the flight trajectories of the square plate fragments are very sensitive to the position of the mass eccentricity. For example, at the initial wind attack angle of 30° and 60°, when the position of the centre of mass is -0.3*l*, their flight trajectories are higher than those of fragments with uniform mass distribution, which will lead to the flight distance of the fragments being farther, resulting in a larger radius of influence. However, when the initial wind attack angles are 120° and 150°, the flight trajectories of the debris are lower than those of the debris with uniform mass distribution when the position of the centre of mass is -0.3*l*. In general, the shift of the centre of mass to different sides of the plate will cause the flight trajectories of the plate to be shifted in different directions.

4. CONCLUSIONS

The mass eccentricity of plate-type windborne debris is worthy to be used as an important parameter in the establishment of a wind disaster model, because the flight trajectories of the debris are very sensitive to the mass eccentric position, and the existence of mass eccentricity will cause the flight trajectories of wind-induced debris to be distributed wider, thereby causing more damage. In general, the larger the deviation of the centre of mass is, the greater the flight trajectory shift. If the centre of mass deviates to different sides of the plate, the flight path will shift up or down in different directions.

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