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A revised aerodynamic model for 3-DOF flight motion of square plates in winds

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SUMMARY:

Plate-like debris such as roof tiles and shingles are very common in strong wind events and could cause considerable damage. Aerodynamic models have been proposed to simulate the 3-degree-of-freedom(3-DOF) (two translational DOF and one rotational DOF) flight motion of square plates. However, they do not necessarily predict the trajectories of plates well. This paper proposes a revised aerodynamic model for the 3-DOF flight motion of square plates based on previous studies. In the revised model, we divide the aerodynamic force and moment on a rotating plate into translational components and rotational components. We model aerodynamic force coefficients and moment coefficients using simple mathematical functions based on the experimental data obtained in the previous studies. In addition, we propose the conditions of using the rotational coefficients obtained from the experiment. The comparison between the numerical results and experiment results of plate trajectories shows better agreements.

Keywords: aerodynamic model, square plates, windborne debris

1. INTRODUCTION

Impact of windborne debris could cause considerable damage to buildings in extreme storms. Plate-like debris is one of the typical types and the focus of this paper. It is important to consider how far they are likely to travel in winds and how fast they are likely to become before impact. In order to simplify these problems, previous studies often focused on the 3-degree-of-freedom (3-DOF) flight motion. The 3-DOF motion in the previous studies and the present paper denotes a special condition in which that the mass center of the plate moves in the plane that contains the wind direction and the gravity direction, and the angular velocity is perpendicular to the plane.

Tachikawa (1983) proposed an aerodynamic model for the 3-DOF flight motion of square plates. He modelled the instantaneous force and moment as the sum of translational components and rotational components. The force and moment coefficients are obtained experimentally. Tachikawa (1983) shows that the numerical results using his model do not present a good agreement with the experimental results in case the plate has an initial angle of attack of 30°. This paper revises Tachikawa's model. The main work of this paper includes: (1) modelling of the aerodynamic data experimentally obtained by Tachikawa (1983) and other researchers with simple mathematical functions; (2) proposal of the necessary conditions of using rotational force and moment coefficients from autorotating tests.

2. REVISED MODEL

2.1. Components of the model

Figure 1 shows a schematic diagram of the 3-DOF motion of a plate. The instantaneous aerodynamic force (lift and drag) and moment acting on a rotating square plate are divided into translational components and rotational components. The translational components are the force and moment acting on a plate with no rotational motion. The rotational components are the force and moment caused by rotational motion. The aerodynamic force and moment can be expressed as the following equations:

$$\boldsymbol{F}_{\mathrm{inst}} = \boldsymbol{F}_{\mathrm{t}} + \boldsymbol{F}_{\mathrm{r}} \ ; \quad \boldsymbol{M}_{\mathrm{inst}} = \boldsymbol{M}_{\mathrm{t}} + \boldsymbol{M}_{\mathrm{r}} \tag{1}$$

where $\boldsymbol{F}_{\mathrm{inst}}$ and $\boldsymbol{M}_{\mathrm{inst}}$ denote the instantaneous force and moment, respectively; $\boldsymbol{F}_{\mathrm{t}}$ and $\boldsymbol{M}_{\mathrm{t}}$ denote the translational components; $\boldsymbol{F}_{\mathrm{r}}$ and $\boldsymbol{M}_{\mathrm{r}}$ denote the rotational components. The translational force and moment coefficients of a square plate have been measured in several previous studies. Holmes et al. (2006) presented a comparison of these results. We only present the modelling of the rotational force and moment in this paper.

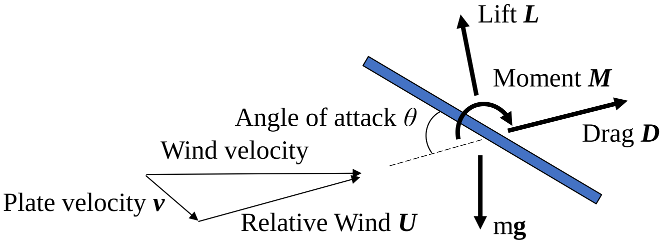

Figure 1. Schematic diagram of the 3-DOF motion of a plate

2.2. Models of rotational force and moment

The rotational force can be divided into a rotational drag and a rotational lift. The rotational drag D_{r}, the rotational lift L_{r} and the rotational moment M_{r} may be modelled using the following equations:

$$D_{\mathrm{r}} = (\rho|\boldsymbol{U}|^2/2)AC_{\mathrm{Dr}} \ ; \ L_{\mathrm{r}} = (\rho|\boldsymbol{U}|^2/2)AC_{\mathrm{Lr}} \ ; \ M_{\mathrm{r}} = (\rho|\boldsymbol{U}|^2/2)AlC_{\mathrm{Mr}} \tag{2}$$

where $\boldsymbol{U}$ is the relative wind velocity (wind velocity minus plate velocity); A is the area of the plate; l is the length of the plate; C_{Dr}, C_{Lr} and C_{Mr} are the rotational drag coefficient, rotational lift coefficient and rotational moment coefficient, respectively.

Tachikawa (1983) measured the aerodynamic force and moment on a rotating square plate through autorotating tests. In these tests, driven by the wind, the plate passively rotates about a fixed axis perpendicular to the flow stream. The angular velocity increases from zero, then reaches a peak value and maintains a steady state. Tachikawa (1983) obtained the relation between the average rotational coefficients, $\overline{C_{\mathrm{Dr}}}$, $\overline{C_{\mathrm{Lr}}}$ and $\overline{C_{\mathrm{Mr}}}$ and the angular velocity ω via the autorotating tests. The results are shown in Figure 2. In the figure, ω_0, $\overline{C_{\mathrm{Dr0}}}$ and $\overline{C_{\mathrm{Lr0}}}$ are the angular velocity, rotational drag coefficient and rotational lift coefficient in the steady state, respectively. Tachikawa (1983) did not obtain the data for ω/ω_0<0.3. He assumed that when ω/ω_0<0.3, $\overline{C_{\mathrm{Dr}}}$, $\overline{C_{\mathrm{Lr}}}$ and $\overline{C_{\mathrm{Mr}}}$ increase from 0 as ω/ω_0 increases from 0 in his model.

However, Bustamante and Stone (1969) found that the plate would not autorotate when ω/ω_0 is too small, and $\overline{C_{\mathrm{Mr}}}$ is a small negative value. Based on the results by Bustamante and Stone (1969), we assume that C_{Dr}, C_{Lr} and C_{Mr} are 0 for $\omega/\omega_0<0.1$. The models are expressed as the following equations.

$$\frac{C_{\mathrm{Lr}}}{C_{\mathrm{Lr0}}}\left(\frac{C_{\mathrm{Dr}}}{C_{\mathrm{Dr0}}}\right)=\begin{cases}0 & (\omega/\omega_0<0.1)\\ -\ln(\omega/\omega_0)/\ln(0.1)+1 & (\omega/\omega_0\geq 0.1)\end{cases}\tag{3}$$

$$C_{\mathrm{Mr}}=\begin{cases}0 & (\omega/\omega_0<0.1)\\ 0.08(-0.99\ln(\omega/\omega_0)/\ln(0.1)-(\omega/\omega_0)^2+1) & (\omega/\omega_0\geq 0.1)\end{cases}\tag{4}$$

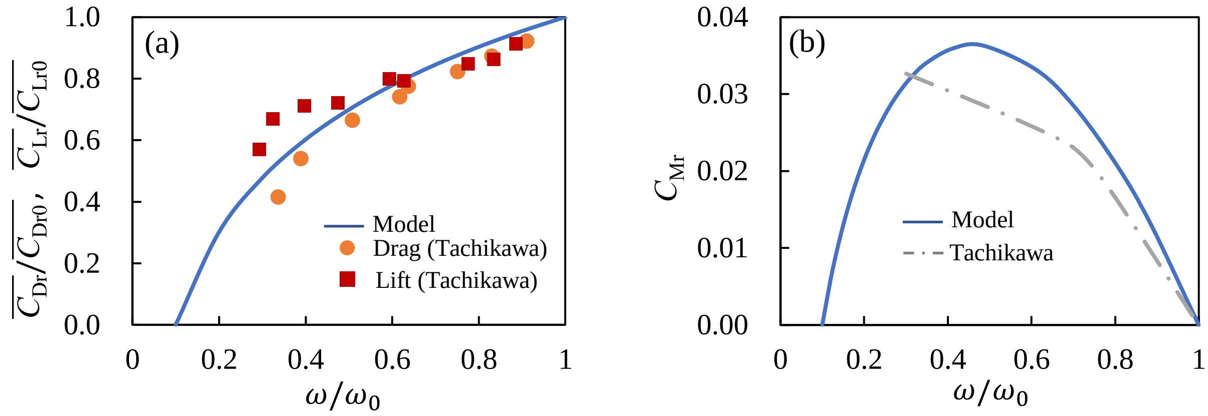

Figure 2. Rotational aerodynamic coefficients against nondimensional angular velocity

2.3. Conditions of using the models of C_{Dr}, C_{Lr} and C_{Mr} (Equation (3) and (4))

Tachikawa (1983) assumed the models of C_{Dr}, C_{Lr} and C_{Mr} based on the experimental data can be used for all conditions. However, this may not be precise. Smith (1971) suggested that the rotational effects may be mainly attributed to the delay of the leading edge vortex. Based on Smith (1971)'s observations, this phenomenon can be explained in the following way. When a plate starts to rotate from a small angle of attack, a vortex at the leading edge is induced. This leading edge vortex creates an aerodynamic moment that support autorotation due to the low pressure at its core. Then, the accelerating rotation delays the separation of the leading edge vortex. As a result, the average angular velocity over one cycle of tumbling continues to increase until the steady state is reached. It can be concluded that the happening of the delay of the leading edge vortex require two necessary conditions. First, the plate rotates at a small angle of attack. Second, the plate is in accelerating rotation. Therefore, we propose the conditions of using the models of C_{Dr}, C_{Lr} and C_{Mr} (Equation (3) and (4))in the revised model: $|\theta|\leq 20°$ and $\boldsymbol{\omega}\cdot\boldsymbol{M}_{\mathrm{t}}>0$. C_{Dr}, C_{Lr} and C_{Mr} are assumed to be 0 until the two conditions are fulfilled.

3. VALIDATION OF THE REVISED MODEL

We performed free flight experiments of a square plate in wind tunnel to validate the revised model. The wind flow is uniform, and the wind velocity is 8 m/s. We used a square wooden plate with a side length of 60 mm, a thickness of 3 mm, and a mass of 6.6 g. The plate was released from a height of 0.55 m. The initial angle of attack θ_0 is changed in each experiment and have four values, 15°, 30°, 60° and 90°. Two digital cameras were used to record the flight trajectories. Then, the recordings were input into the motion analysis software (DIPP-MotionV/3D) to estimate the position, orientation of the plates in flight; then, on this basis, velocity, and angular velocity. We performed an accuracy test, and the result shows that the average error of the coordinates of the tracking markers was 0.16 cm. A supporting system is used to control the initial orientation of the plate. To avoid the influence of the supporting system, the numerical simulation starts after the plate flew a small distance (about 5 cm). Figure 3 shows the results for $\theta_0 = 30°$. The results of the revised model show a better agreement with the experimental data than Tachikawa's model. Figure 3(a) shows that Tachikawa's model overestimates the angular velocity, and consequently, overestimates the plate velocity and flight distance in X direction (Figure 3 (b) and (c)), because the rotational drag increases as the angular velocity increases.

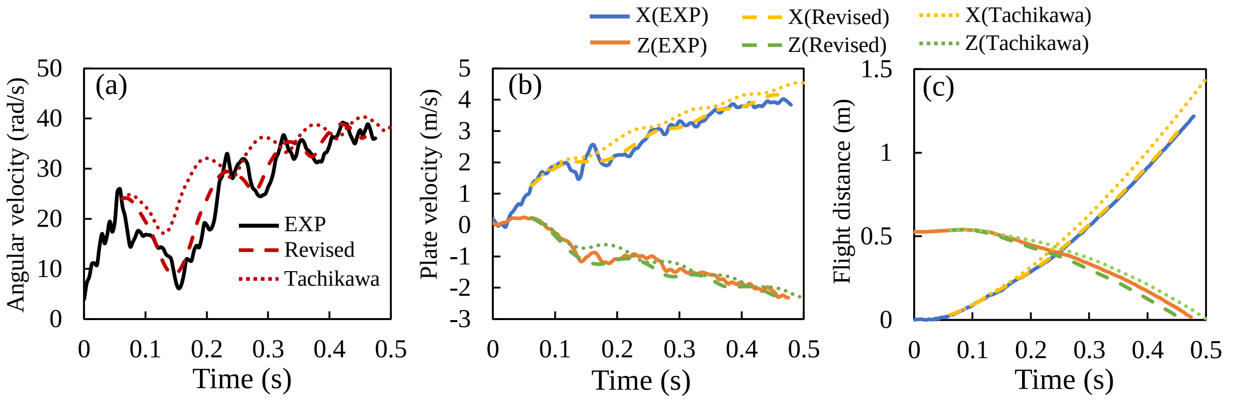

Figure 3. Comparison of experimental results and numerical results of a plate with $\theta_0 = 30°$

4. CONCLUSIONS

This paper proposed a revised aerodynamic model for the 3-DOF flight motion of square plates based on Tachikawa (1983)'s model. The aerodynamic force and moment are divided into translational components and rotational components. We modeled the rotational aerodynamic coefficients by integrating the experimental results of the previous studies. We also proposed the necessary conditions of using the rotational aerodynamic coefficients obtained from experiments. We validated the revised model by comparing the experimental results and numerical results of trajectories of a square plate. The results show that the revised model can better predict the trajectories of the square plate than Tachikawa's model.

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