# The Vortices in the Wake of a Falling Paper Card

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Leaves, tree seeds, and paper cards that fall through the air are simple, everyday systems with complex trajectories and beautiful vortex wakes. Research on such objects that fall freely in a fluid was pioneered by James Clerk Maxwell who proposed a model to explain periodic motion of a tumbling paper card already in 1854 [1]. The problem of a freely falling plate has things in common with diverse problems such as tree seed dispersal by wind as studied by McCutchen [2] and fixed axis auto-rotation as investigated in wind-tunnel experiments with plates and polygonal objects by Skews [3]. The Reynolds number of a paper card falling in air is about one thousand, which is comparable to the Reynolds number for the flow around the wings of a large insect in flight [4]. The unconstrained dynamics of freely falling plates makes it possible to deduce the fluid forces on the plates directly from measured trajectories and thereby to test models of fluid forces that are relevant for intermediate Reynolds number aerodynamics, including the aerodynamics of insect flight.

In this presentation I review the main experimental and theoretical findings by Andersen, Pesavento, and Wang about the trajectories of falling plates and the fluid forces that govern their dynamics [5, 6], and I present new experimental visualisations of the vortex structures in the wakes of falling plates. In particular I discuss measured trajectories and vortex wakes of falling plates with different thickness to width ratios, and I present a simple quasi-steady model of the fluid forces with both rotational and translational lift contributions [7]. Plates with small thickness to width ratio oscillate from side to side (flutter) whereas plates with large thickness to width ratio rotate and drift sideways (tumble) as shown in figure 1. The importance of the thickness to width ratio, or equivalently the dimensionless moment of inertia, was originally pointed out by Willmarth and coworkers [8] and investigated by Belmonte and coworkers in a quasi two-dimensional experiment [9]. I discuss this parameter dependence further and show that plates in the transition region between periodic fluttering and periodic tumbling display unpredictable motion that depends sensitively on initial conditions as shown in figure 1. The flow visualisations of periodic fluttering and periodic tumbling reveal that von Kármán like vortex streets are formed during the gliding segments of the trajectories and that large vortices are shed at the turning points. I discuss these vortex structures and their importance for the fluid forces and torques that govern the dynamics of the falling plates.

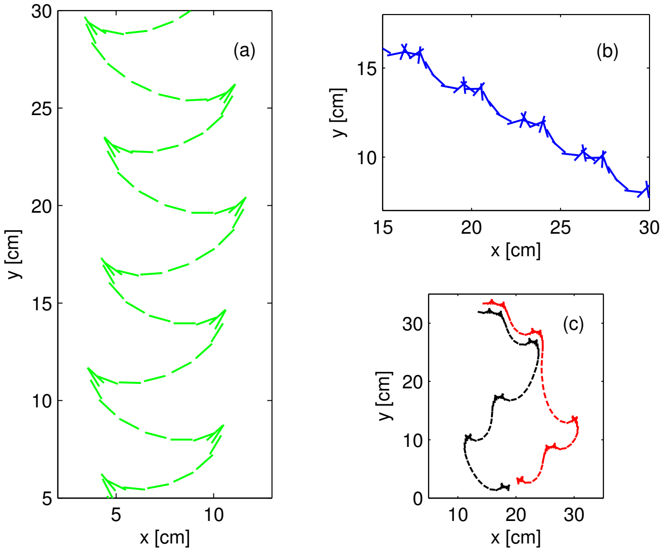

Figure 1: Measured trajectories of freely falling plates with different thickness to width ratios: (a) periodic fluttering of a plate with thickness to width ratio 1/14, (b) periodic tumbling of a plate with thickness to width ratio 1/5, and (c) two examples of unpredictable and apparently chaotic trajectories in the transition region between fluttering and tumbling for a plate with thickness to width ratio 1/6.

# References

[1] J. C. Maxwell, Cambridge and Dublin Math. J. **9**, 145-148 (1854).

[2] C. W. McCutchen, Science **197**, 691-692 (1977).

[3] B. W. Skews, Nature **352**, 512-513 (1991).

[4] Z. J. Wang, Annu. Rev. Fluid Mech. **37**, 183-210 (2005).

[5] A. Andersen, U. Pesavento, and Z. J. Wang, J. Fluid Mech. **541**, 65-90 (2005).

[6] A. Andersen, U. Pesavento, and Z. J. Wang, J. Fluid Mech. **541**, 91-104 (2005).

[7] U. Pesavento and Z. J. Wang, Phys. Rev. Lett. **93**, 144501 (2004).

[8] W. W. Willmarth, N. E. Hawk, and R. L. Harvey, Phys. Fluids **7**, 197-208 (1964).

[9] A. Belmonte, H. Eisenberg, and E. Moses, Phys. Rev. Lett. **81**, 345-348 (1998).