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Further experimental evidence of vortex splitting

By P. FREYMUTH, W. BANK AND M. PALMER
Department of Aerospace Engineering Sciences, University of Colorado,
Boulder, Colorado 80309

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Further experimental evidence of vortex splitting in wake flows is presented. Streakline visualizations reveal the range of conditions and the phenomenology of this novel process.

1. Introduction

The first experimental evidence of the process of vortex splitting has been presented by Freymuth, Bank & Palmer (1984), in the accelerating flow around an airfoil, starting from rest. This novel two-dimensional process by which a vortex gets stretched and then splits into two parts while interacting with another vortex of opposite sign has been predicted by Moore & Saffman (1971) (see also Saffman & Baker 1979) on general theoretical grounds and by Christiansen & Zabusky (1973) on the basis of computer experiments for unstable vortex streets.

In this paper we extend our previous investigation by scanning the experimental parameter range available to us for the process of vortex splitting. This range involves various geometries and Reynolds numbers for accelerated flow starting from rest, as well as for steady upstream flow. Sequences of movie frames in which vortex patterns are visualized document the phenomenology of the process.

While we concentrate on vortex splitting, the potential relevance of this and other vortical interactions for the search of turbulent flow structures has been pointed out by Saffman & Baker (1979).

2. Experimental procedures

Flow visualization in wakes behind selected bodies were conducted in a wind tunnel with 0.9 m by 0.9 m square cross-section as described in detail by Freymuth, Bank & Palmer (1983*a*, *b*). The tunnel allowed a uniform flow acceleration $a = 2.4\ \mathrm{m/s^2}$ for 5 s, starting from rest. Operation in a steady speed mode up to 12 m/s was also possible.

Visualization of vortical patterns was by a streakline method using liquid titanium tetrachloride as smoke-generating agent on the body surface.

Movies of vortex patterns were taken with a Bolex camera at a rate up to 64 frames/s and the pattern sequences were examined for the process of vortex splitting.

3. Experimental results

3.1. *Accelerating flow around an airfoil starting from rest*

Our flow-visualization experiments concentrate mainly on this configuration, since it exhibits vortex splitting most prominently. We used airfoils with NACA 0015 profile. The vortical pattern development visualized by us depends on three parameters: the angle of attack α, a dimensionless time t^* and a Reynolds number R. We define

$$t^* = ta^{\frac{1}{2}}c^{-\frac{1}{2}} = tt_c^{-1}, \quad (1)$$

$$R = a^{\frac{1}{2}}c^{\frac{3}{2}}\nu^{-1}, \quad (2)$$

where t is time from flow startup, a is the constant flow acceleration, c is the airfoil chord length and ν is the air kinematic viscosity. In our experiments dependence on α was found by adjusting this angle to a desired value, dependence on t^* was found by taking a movie sequence, and Reynolds number dependence was found using airfoils of different chord lengths while a and ν remained constant.

The process of vortex splitting will be shown in the figures. Each figure consists of a sequence of movie frames, arranged in columns from top to bottom and the columns ordered from left to right. Time between frames is Δt, time from flow startup to the first frame shown is t_1, corresponding to dimensionless quantities $\Delta t^* = \Delta t/t_c$ and $t_1^* = t_1/t_c$.

Flow in the figures is always from left to right. The angle of attack α is from the horizontal upward, positioning normally the round leading edge of the airfoil upward and to the left of the sharp trailing edge.

Freymuth *et al.* (1984) showed vortex splitting at $\alpha = 60°$, $R = 350$. Figure 1 shows the process occurs also at $\alpha = 90°$, $R = 350$. In column 1 the formation of vortex loops occurs. In column 2 the leading-edge vortex loop flattens under the influence of the trailing-edge vortex, and then splits into two. The left of these vortices gets augmented by additional vorticity from the leading edge which then splits the trailing-edge vortex below it into two in column 3. In contrast, at 60° the trailing-edge vortex was left nearly intact.

Figure 2 shows vortex splitting at $\alpha = 20°$, $R = 350$. At this angle vorticity leaves the trailing edge and forms two vortex tongues prior to interaction with the evolving leading-edge vortex, which then gets split rapidly. Below 20° vortex splitting becomes difficult to ascertain.

Figure 3 shows vortex splitting to occur even if the airfoil orientation is reversed, i.e. the sharp edge of the airfoil is facing upstream. We have $\alpha = 60°$, $R = 124$. The top vortex loop flattens the bottom vortex and splits it in column 2, while being flattened. The flattened top loop folds again before it is flattened further and split by the second bottom vortex, creating a stunning pattern. Later on the process of vortex splitting gets less prominent and ceases toward the bottom of column 3, where vortices are alternately shed from leading and trailing edges, eliminating the need for splitting.

We conclude that vortex splitting can occur at any angle sufficiently high for the airfoil to act as a bluff body.

Next we probe a considerable Reynolds number range for the process of vortex splitting.

Figure 4 shows vortex splitting at $\alpha = 80°$, $R = 44$, where it occurs for the first three top vortices and, less clearly visualized, also for the first three bottom vortices, after which the alternate-shedding stage is reached in column 3.

Figure 5 shows vortex splitting at the same angle $\alpha = 80°$ but at a much increased Reynolds number $R = 5200$. The flow starts out more complex, i.e. the leading- and trailing-edge vortex filaments now form vortex groups rather than single vortices and splitting now occurs for these vortex groups during their transition to turbulence. The first trailing-edge vortex group gets flattened by the influence of the leading-edge

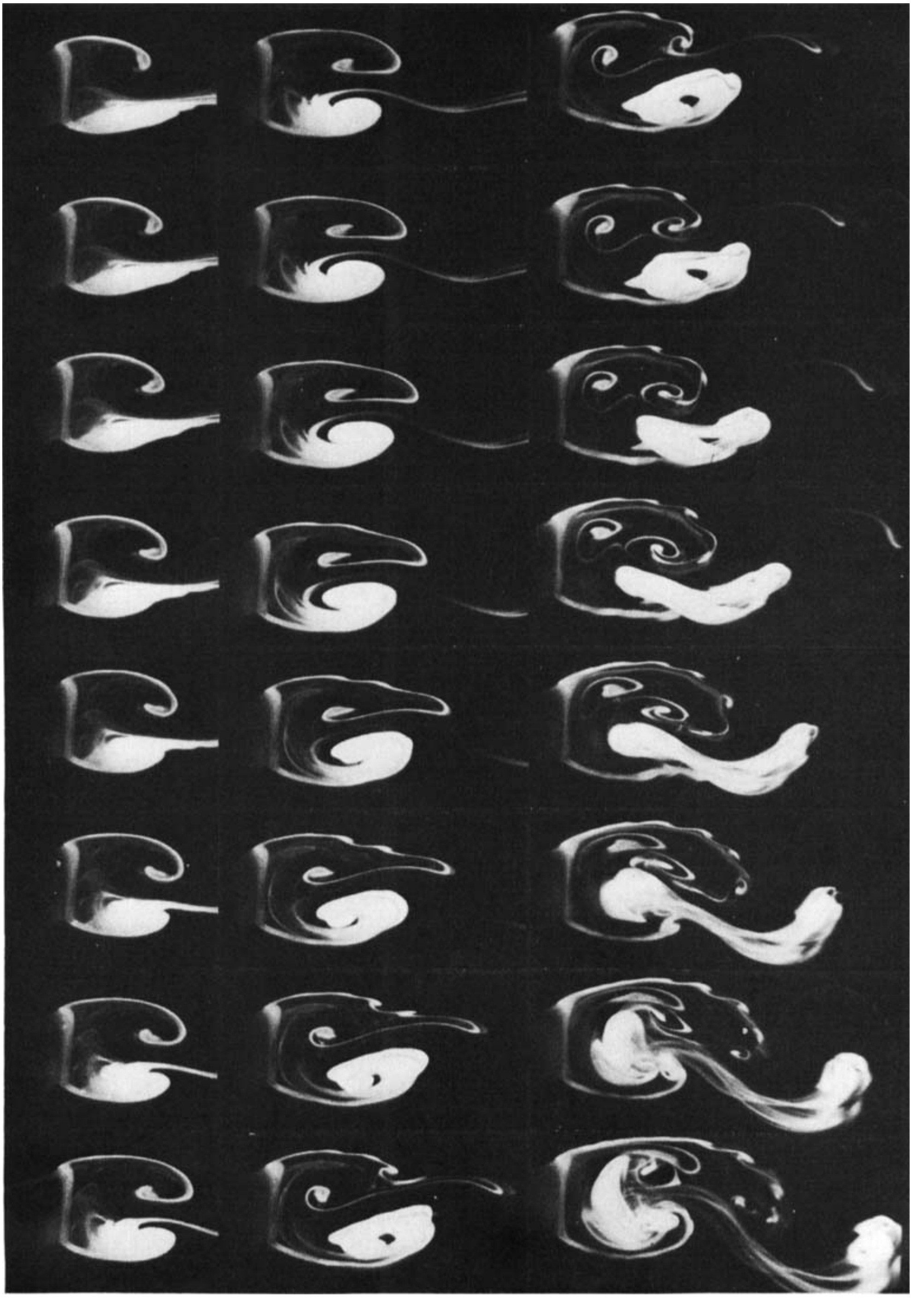

FIGURE 1. Accelerated flow around an airfoil. $\alpha = 90°$, $R = 350$, $t_1^* = 5.6$, $\Delta t^* = 0.15$, $c = 2.54$ cm, 64 frames/s.

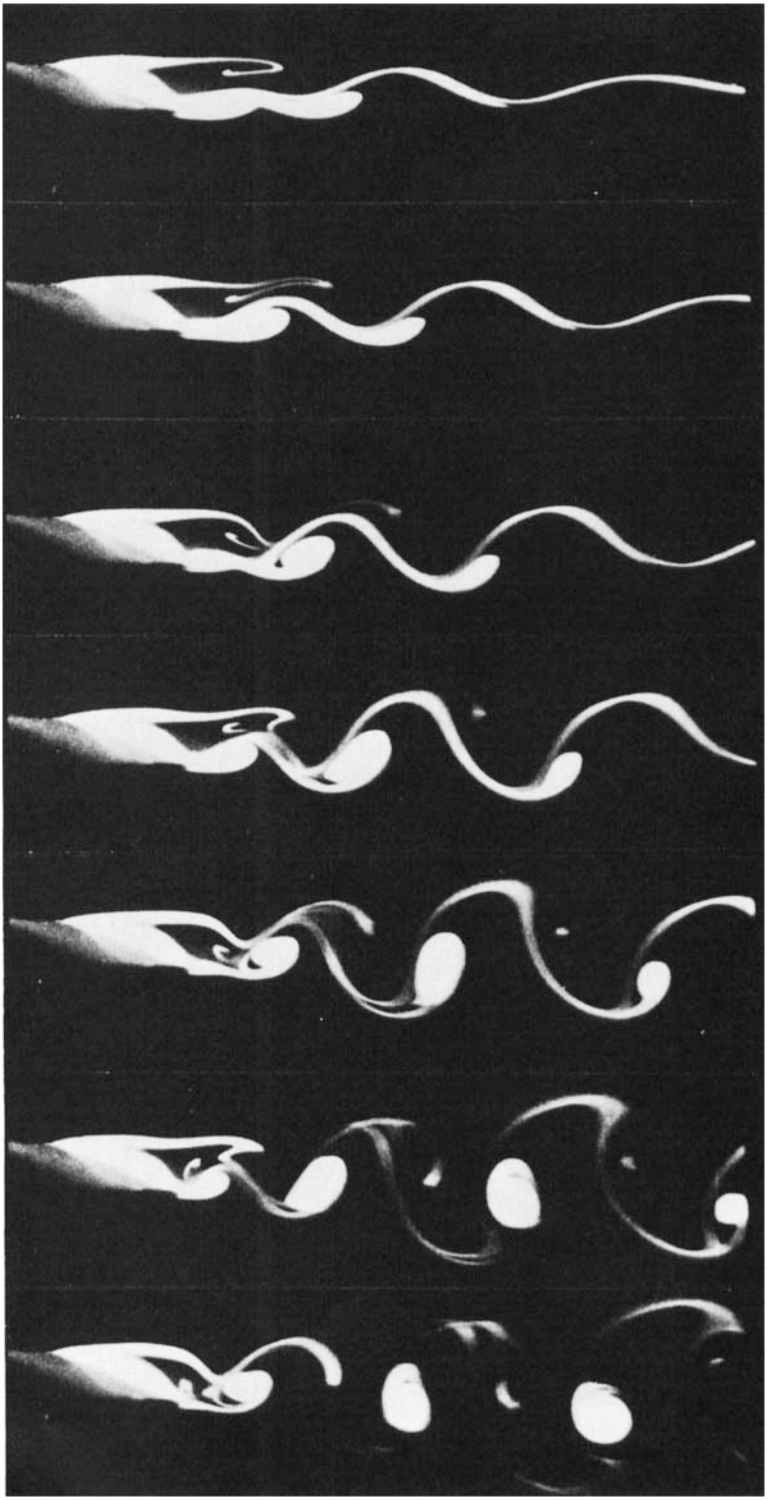

FIGURE 2. $\alpha = 20°$, $R = 350$, $t_1^* = 8.2$, $\Delta t^* = 0.15$, $c = 2.54$ cm, 64 frames/s.

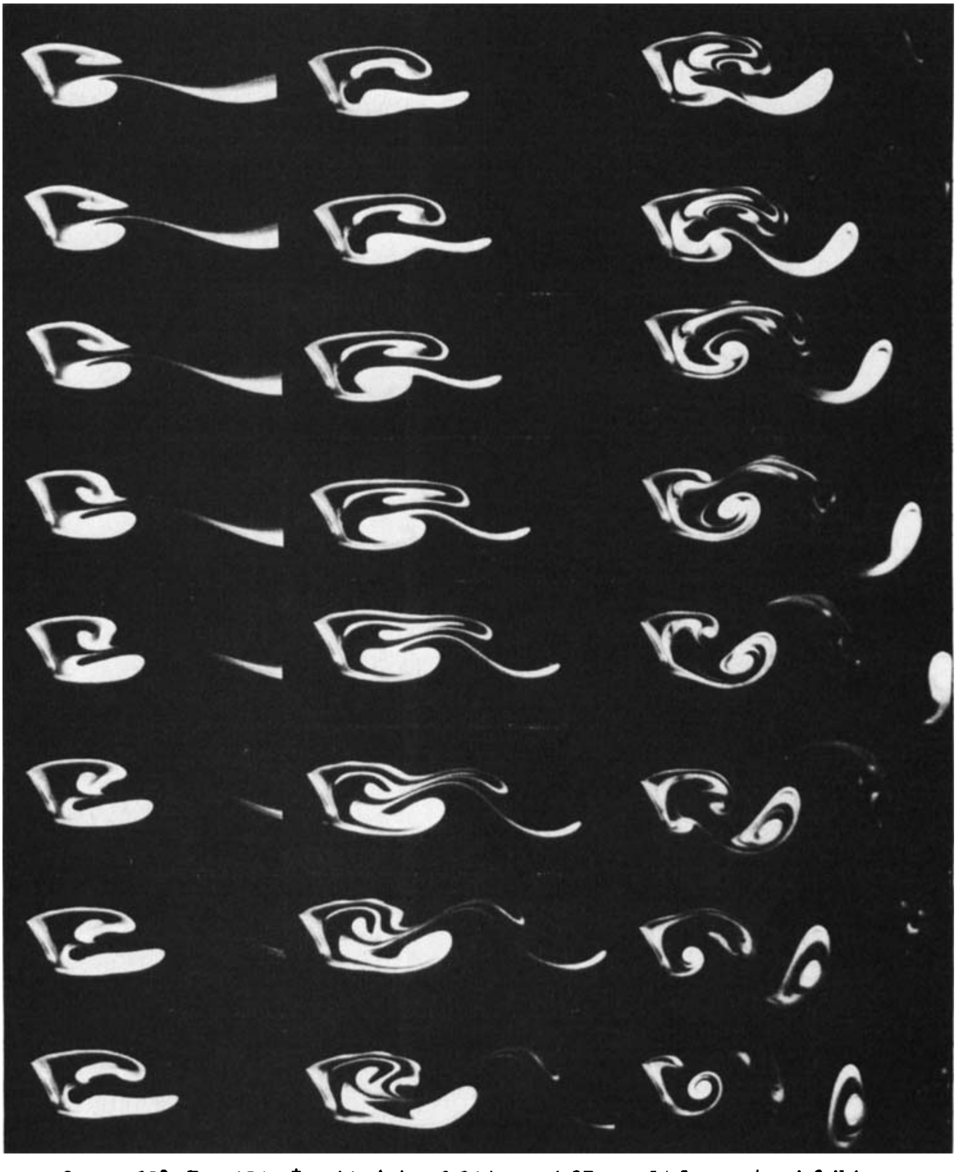

FIGURE 3. $\alpha = 60°$, $R = 124$, $t_1^* = 11$, $\Delta t^* = 0.214$, $c = 1.27$ cm, 64 frames/s, airfoil in reverse.

vortex in column 2, then splits into two parts in column 3. Thereafter the leading-edge vortex group is split by the second, turbulent trailing-edge vortex before the alternate-vortex-shedding stage is reached.

In addition to the leading- and trailing-edge vortex groups, a small secondary vortex develops, barely visible in figure 5 as a white triangle near the leading edge starting in column 2. To obtain a more acceptable resolution of this vortex and its interaction with the primary vortex group it was necessary to film a closeup sequence near the leading edge, to introduce smoke more sparingly and to double the frame rate. This is shown in figure 6, where the first frame corresponds in time to the first frame of column 3 in figure 5. It can be seen that the secondary vortex with counterclockwise

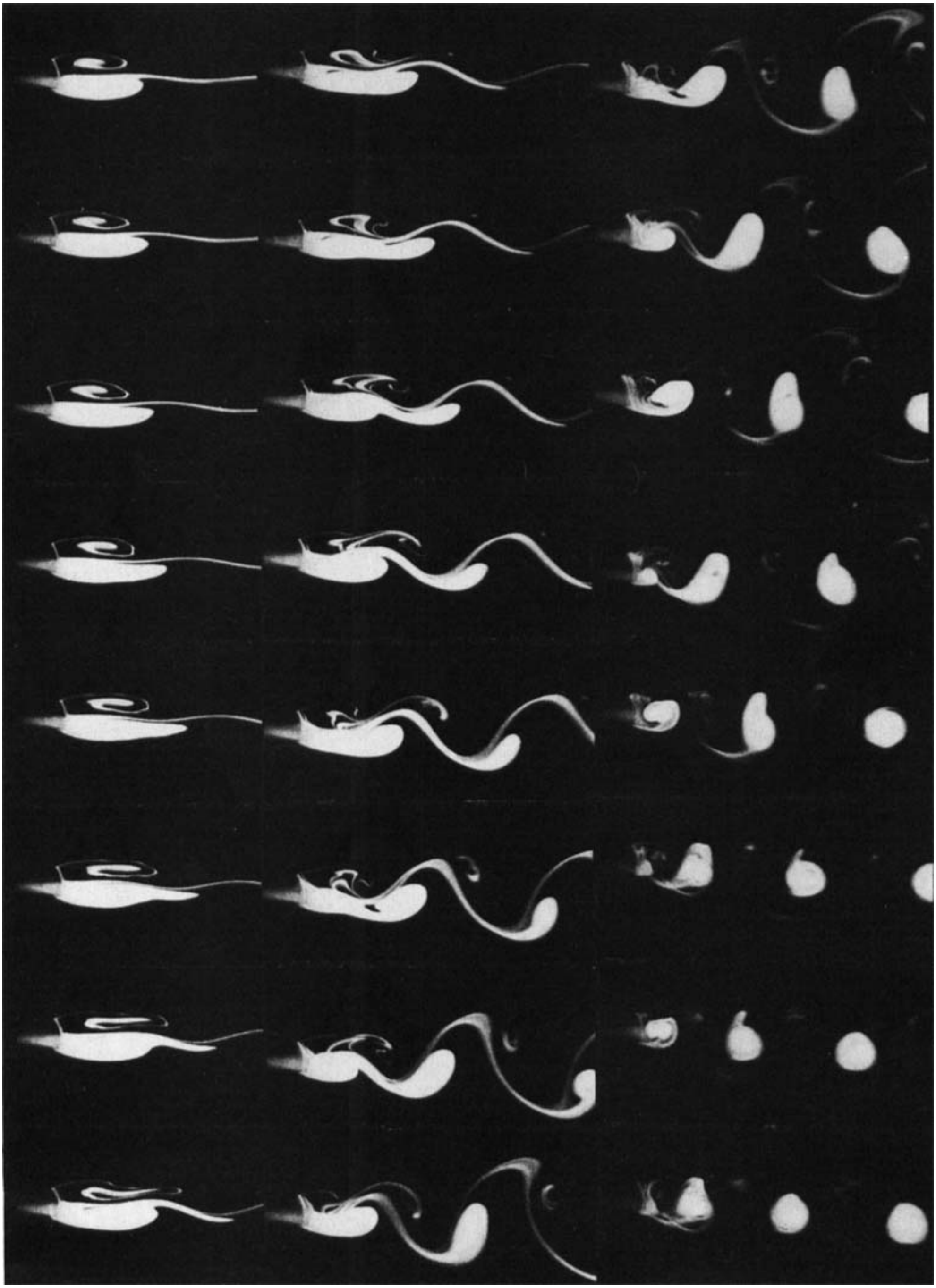

FIGURE 4. $\alpha = 80°$, $R = 44$, $t_1^* = 9.8$, $\Delta t^* = 0.306$, $c = 0.63$ cm, 64 frames/s.

rotation gets completely stretched out by the influence of the primary vortex group without a chance of forming new vortices. We call this new process vortex shredding, another variant of the concept of tearing apart of a vortex as introduced by Moore & Saffman (1971).

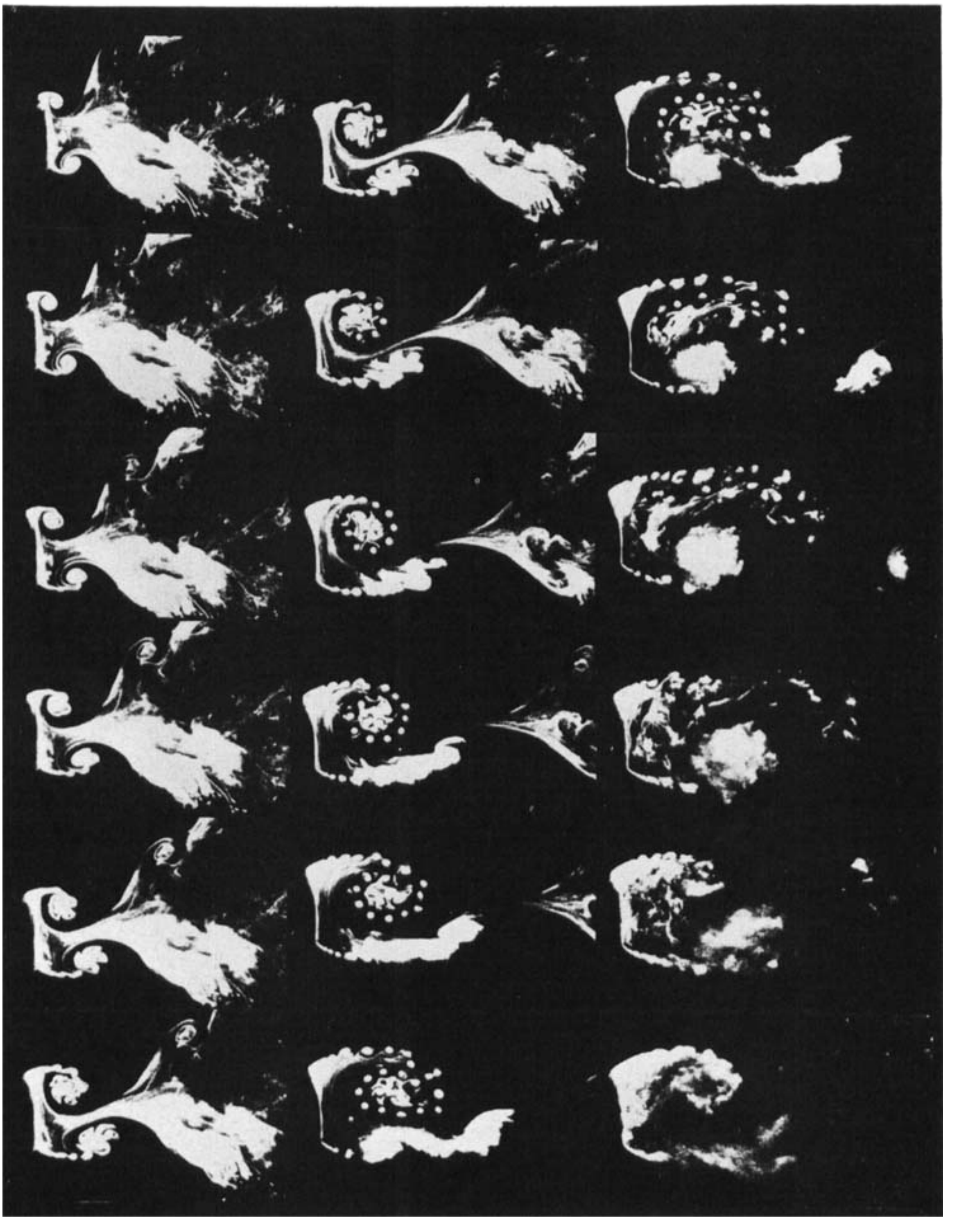

FIGURE 5. $\alpha = 80°$, $R = 5200$, $t_1^* = 1.81$, $\Delta t^* = 0.25$, $c = 15.2$ cm, 16 frames/s.

In figure 7 we show the splitting of a secondary vortex by a primary vortex, which occurs close to the airfoil surface in column 2, at $\alpha = 20°$ and $R = 5200$.

3.2. *Some additional experiments*

The process of vortex splitting was also observed by us in the accelerating flow around a circular cylinder 2.54 cm diameter.

Vortex splitting occurs in flows with nonconstant acceleration after start from rest, as an experiment showed in which the acceleration increased linearly with time.

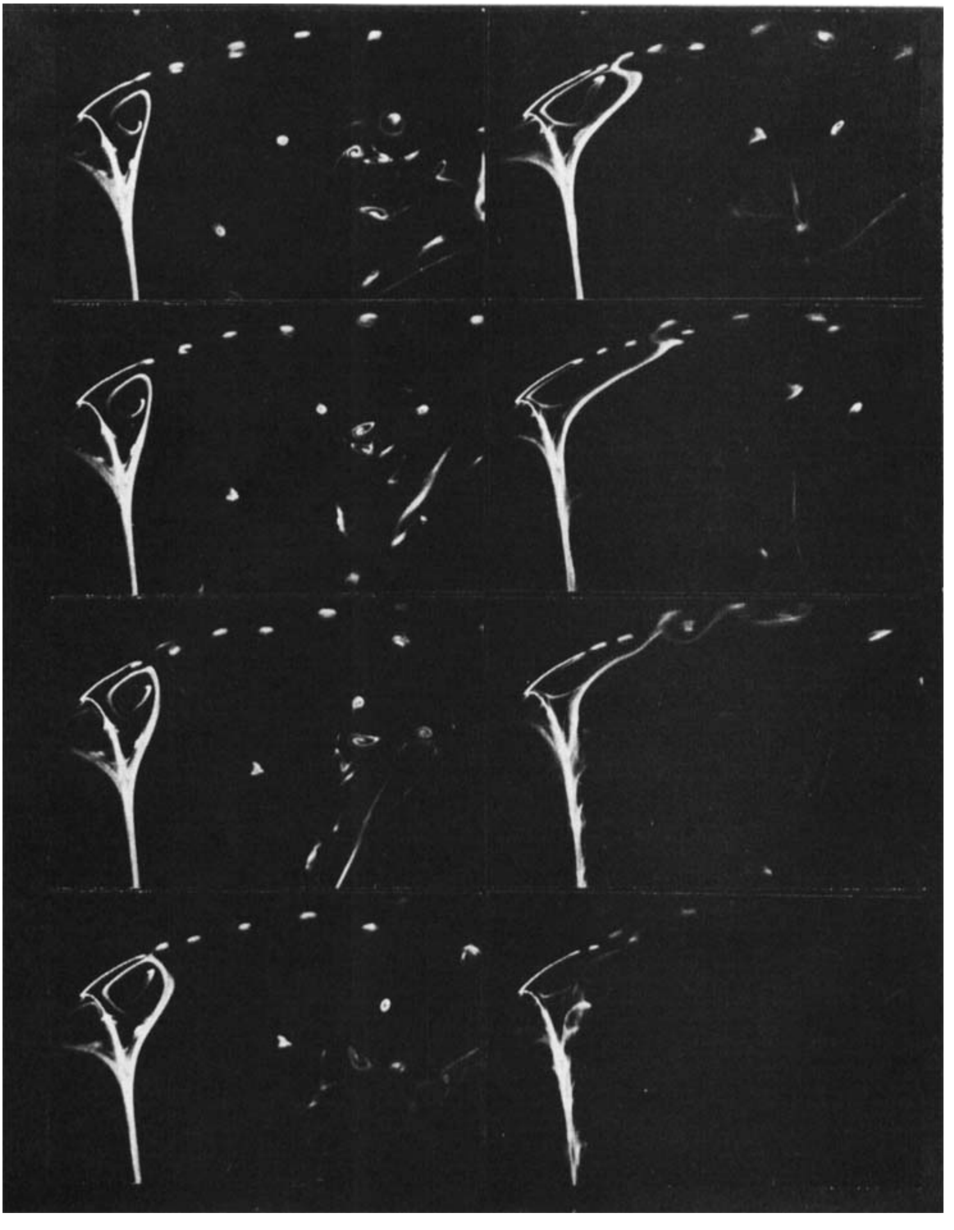

FIGURE 6. $\alpha = 80°$, $R = 5200$, $t_1^* = 4.75$, $\Delta t^* = 0.125$, $c = 15.2$ cm, 32 frames/s, closeup view of area near leading edge.

We also searched for vortex splitting in flows with steady free-stream conditions. The flow around a circular cylinder was in an alternate-vortex-shedding stage without evidence of splitting, but for an airfoil the shedding of the leading-edge vortex exhibited weak splitting, labelled by us 'vortex nipping'. This is shown in figure 8 at $\alpha = 40°$ and for a Reynolds number $R_u = 350$, which is based on free-stream velocity. Only a small part (less than 10%) of the leading-edge vortex is nipped off and incorporated into the next vortex.

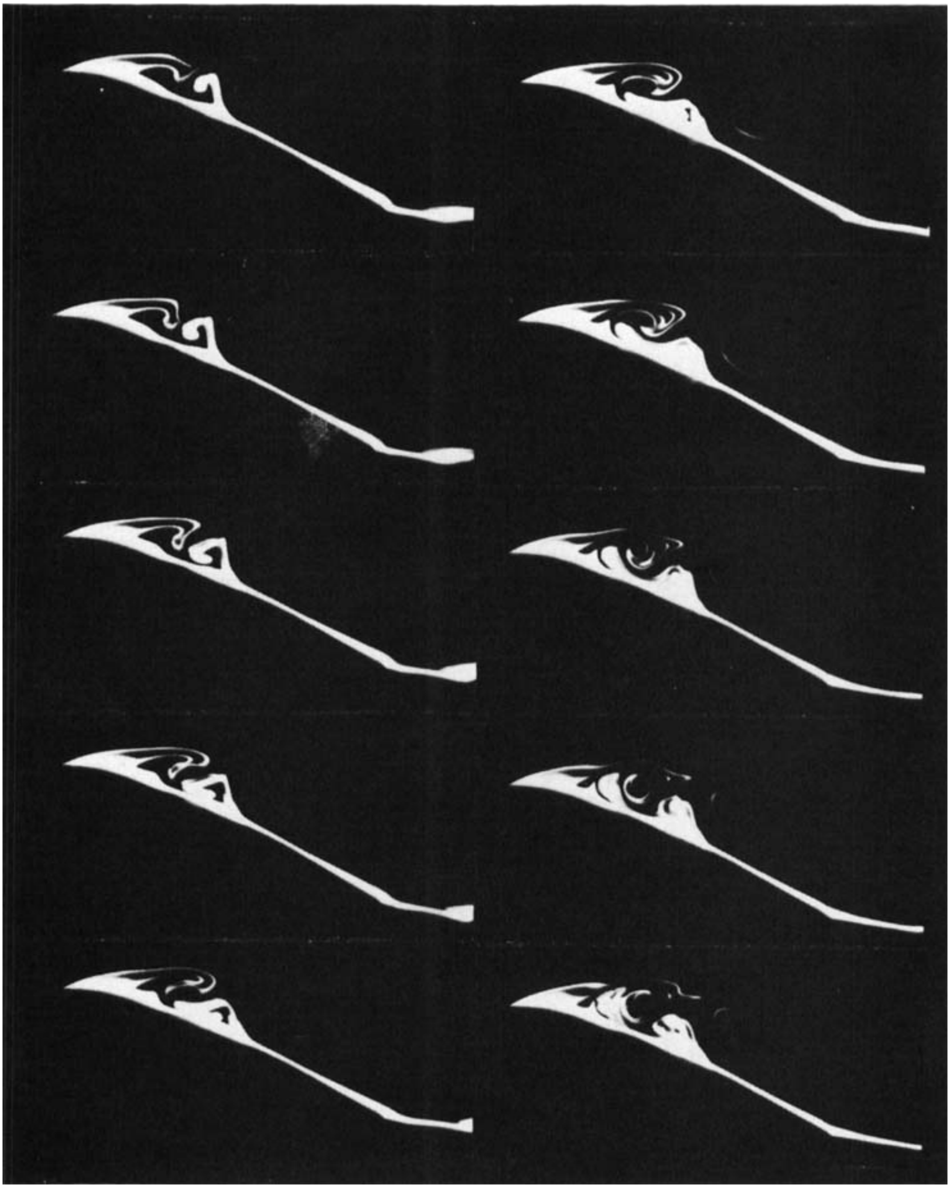

FIGURE 7. $\alpha = 20°$, $R = 5200$, $t_1^* = 4.8$, $\Delta t^* = 0.0625$, $c = 15.2$ cm, 64 frames/s.

Does impulsively started flow around bluff bodies exhibit vortex splitting beyond nipping? While we cannot address this question experimentally, impulsive flow around elliptical cylinders visualized by Taneda (1977) and around airfoils visualized by Izumi & Kuwahara (1983) do not indicate this process, nor do the computer experiments for impulsive flow around elliptic cylinders by Lugt & Haussling (1974).

4. Conclusions

We have visualized the dramatic interaction of vortex splitting in accelerating flow behind airfoils, starting from rest for a considerable range of α, R and t^*. We hope

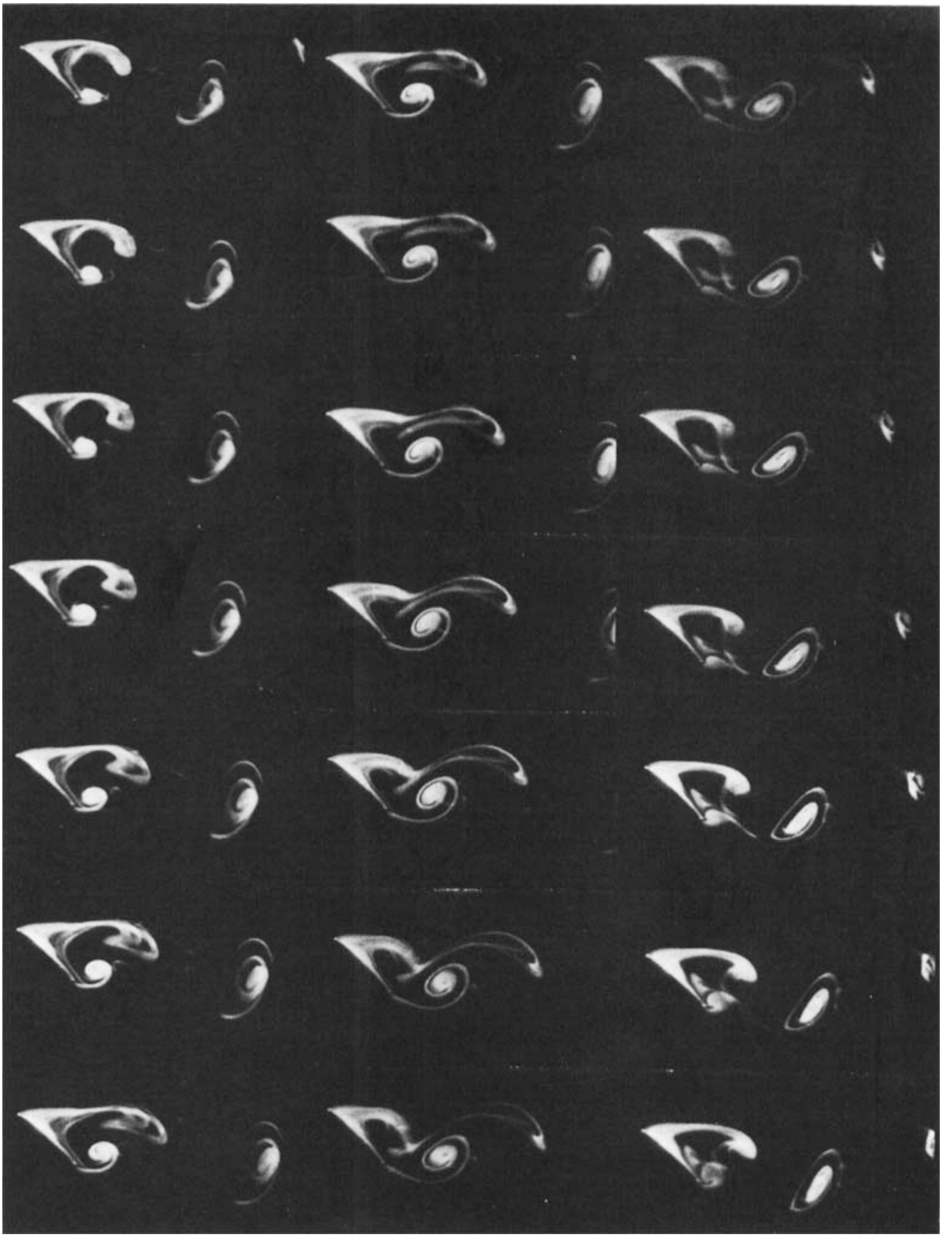

FIGURE 8. Flow around an airfoil at constant freestream velocity, $\alpha = 40°$, $R_u = 350$, $c = 2.54$ cm, 32 frames/s.

these experiments pave the way for meaningful computer experiments which allow a more quantitative understanding of this process.

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