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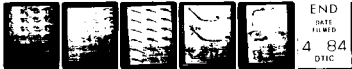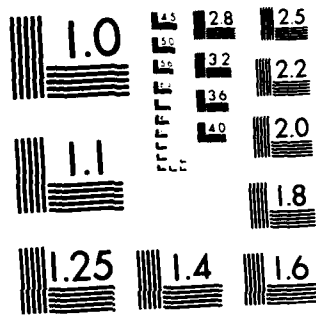   AEROSPACE ENGINEERING SCIENC.. P FREYMUTH ET AL.
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Acclerating flow around an airfoil was visualized using smoke technique. The flow started from rest and acceleration was kept constant for 5 seconds. Movies and single-frame photographs of the developing flow were taken for various angles of attack. The developing vortes patterns are interpreted as the elaborate initiation of an unsteady turbulent vortex street.

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Visualization of accelerating flow around an airfoil at high angles of attack

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Summary: Accelerating flow around an airfoil was visualized using smoke technique. The flow started from rest and acceleration was kept constant for 5 seconds. Movies and single-frame photographs of the developing flow were taken for various angles of attack. The developing vortex patterns are interpreted as the elaborate initiation of an unsteady turbulent vortex street.

Sichtbarmachung einer beschleuningten Strömung um einen Tragflügel bei hohen Anstellwinkeln.

Übersicht: Die beschleunigte Strömung um einen Tragflügel wurde mit Rauch sichtbar gemacht. Die Strömung begann aus der Ruhe und ihre Beschleunigung wurde für 5 Sekunden aufrecht erhalten. Filme und Einzelaufnahmen der sich entwickelnden Strömung wurden für verschiedene Anstellwinkel erhalten. Die Wirbelmuster werden als Einleitung einer instationaren turbulenten Wirbelstraße gedeutet.

1. Introduction

Periodic flows around airfoils at high angles of attack (angles higher than the static stall angle) have received considerable attention during the last decade, as the reviews by McCroskey [1], [2] attest.

Our investigation probes another fundamental and largely unknown unsteady flow field around a stationary airfoil at high angles of attack that develops when, starting from rest, the flow far from the airfoil maintains a constant acceleration over the time of observation. Our aim is the visualization and photographic documentation of basic unsteady phenomena in this flow configuration.

Somewhat related, although different in configuration and scope, are the investigations by Wedemeyer [3] and Pierce [4] into the vortex structure near plates that have been set into motion rather impulsively, and the investigations by Taneda [5] on an impulsively started elliptic cylinder at high angles of attack. It is noteworthy that visualization of unsteady flows around objects goes back to Prandtl [6].

Before we turn to the experiments a few dimensional considerations are helpful. An inviscid characteristic time scale t_c will be defined as the time needed for the starting flow to travel half the distance of the chordlength c, subject to the acceleration a. The velocity of the flow reached at this time will be used as characteristic velocity scale V_c. Therefore

$$(1.1) \quad t_c = c^{\frac{1}{2}} a^{-\frac{1}{2}}$$

$$(1.2) \quad V_c = c^{\frac{1}{2}} a^{\frac{1}{2}}$$

An appropriate Reynolds number is defined by

$$(1.3) \quad R = a^{\frac{1}{2}} c^{3/2} \nu^{-1} = V_c c \nu^{-1}$$

where ν is the kinematic viscosity in air. For a fixed Reynolds number the main dimensionless parameter on which the flow problem in dimensionless presentation depends is the angle of attack α. In our investigations c = 15.2 cm and a = 2.4 m/sec^2 and consequently t_c = 0.25 sec, V_c = 0.61m/sec and R = 5300. It should be noted that the sustaining time for acceleration of 5 sec obtained in our wind tunnel is much larger than t_c.

2. Experimental setup

We succeeded in converting a large, open-return low-turbulence wind tunnel with a 20 m long test section and 0.91 m x 0.91 m cross section

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from steady flow operation to the desired unsteady operation. The tunnel started from rest and then sustained a nearly constant acceleration of 2.4 m/sec^2 (25% of gravity) for 5 seconds. Thereafter, the power to the driving fan was turned off and the flow allowed to come to rest. The tunnel was ready for the next acceleration run within 2 minutes.

A brief description of the wind tunnel control may be in order. The 186 kW electric motor driving the fan was powered from the generator of a Ward-Leonhard system. Power into the fan motor was field controlled at the generator of the Ward-Leonhard system, requiring a field coil current of maximally 2A. For proper flow acceleration, it was found empirically that a current pulse at the field coil followed by a current ramp gave a constant flow acceleration. Pulse duration and ramp slope were experimentally adjusted to give optimum performance with the safety constraint that the maximum current to the fan motor did not exceed 1500 A during the initial pulse. This allowed us to obtain a nearly constant acceleration of 2.4 m/sec^2 for 5 seconds.

We used an airfoil with a chord length c = 15.2 cm and with a symmetric NACA 0015 profile. The airfoils consisted of black anodized aluminum. Airfoil mounting was horizontal; the airfoil was rotated around the quarter chord for angle of attack adjustment from outside the tunnel.

Flow visualization required smoke generation near the upper airfoil surface. Titanium tetrachloride ($TiCl_4$) deposited by means of a brass pipette as a centerstrip (ca. 0.5 cm wide) from the leading to the trailing edge formed a smoke-generating thin liquid film.

For observation and lighting purposes, tunnel top and front walls were made from Plexiglass; back and bottom walls were painted flat black. Lighting was supplied from the top by four projector lamps at 500 W each, and photographing was done from the front side.

Movies were taken with a 16 mm Bolex camera at 64 frames per second. Exposure time per frame was 1/400 second. We used negative ASA 400 films. For improved quality of photographic detail 35 mm single-frame negatives were taken with a Nikon F2 camera at 1/500-second exposure time in separate test runs.

4. Flow visualization

The reader is reminded that all visualization experiments were done with c = 15.2 cm, a = 2.4 m/sec^2, t_c = 0.25 sec and R = 5300. Figure 1

shows a sequence of movie frames in side view at $\alpha = 20^\circ$. Flow is from
left to right. The sequence starts down the left column, then proceeds
to the middle and right columns. The frames proceed in time steps
Δt of 1/16 second. The first frame was taken before startup and the
second frame immediately after startup of the linear velocity ramp.
The centerstrip of smoke at the upper airfoil surface can be seen in
the first frame, as well as smoke remnants from the insertion and with-
drawal of the $TiCl_4$ pipette.

From the second frame on, a vortex sheet leaving the trailing edge
to the right can be seen. The vortex sheet gets lumpy and decays into
small vortices. Meanwhile, vorticity starts to separate near the leading
edge in the form of a tongue (its mirror image on the shiny black airfoil
surface can also be seen). A vortex structure forms which quickly decays
into a large and somewhat amorphous turbulent vortex. The large vortex
then seems to trigger the formation of a large trailing vortex, after
which another diffusive leading edge vortex forms, followed by another
trailing vortex. We interpret our results as the initiation of an
unsteady turbulent vortex street.

Figure 2 shows the initiation of a turbulent vortex street for
$\alpha = 40^\circ$. The formation of a starting vortex and of other vortices from
the trailing edge vortex sheet starts *earlier* and proceeds *faster* than
at $\alpha = 20^\circ$ and this also holds for the formation of the leading edge
vortex. The leading edge vortex gets turbulent and triggers formation
of a large trailing edge vortex. A vortex street has been initiated
within about five characteristic time scales t_c.

Figure 3 shows vortes formation at $\alpha = 60^\circ$. The leading edge
vortex now decays into a vortex group prior to turbulent decay. In
Figure 4 for $\alpha = 80^\circ$ one observes how the trailing edge vortex *structure*
gets "bulldozed" by the leading edge vortex into a rather flat shape
that breaks into two vortices, with the left one starting the next
trailing edge vortex. Additional frames show alternate turbulent
vortex shedding as in previous figures.

In Figure 5 at $\alpha = 90^\circ$, the initial development at the trailing
and leading edges becomes relatively symmetric. The ornamental
vortices in their initial stages now resemble those visualized by
Pierce (4) in flow around the edges of nearly impulsively started plates.

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Figure 6 represents a closeup sequence of the vortex formation and its beginning turbulence near the leading edge for $\alpha = 20°$. This process was not sufficiently resolved in Figure 1. A beautiful vortex triple structure evolves together with its optical mirror image on the airfoil surface. Note the counterrotation of the middle structure and the weak formation of another counterrotating vortex near the apex just prior to turbulent decay.

Figure 7, top and center, shows delicate patterns at $\alpha = 40°$. These enlargements of single frame photographs again reveal the triple structure near the leading edge. Figure 7, bottom, shows the visual effects of triangular shape (left, $\alpha = 60°$) and square shape (right, $\alpha = 80°$).

Figure 8, top, shows the resolution of small vortices at $\alpha = 80°$ into their spiral structures. Figure 8, center ($\alpha = 80°$) and bottom ($\alpha = 90°$) demonstrate the visual contrast between asymmetrical and rather symmetrical patterns.

In conclusion, the initial development of accelerating flow around an airfoil reveals exceedingly complex and stunningly beautiful vortex patterns. It will be a long time before these patterns can be modeled theoretically.
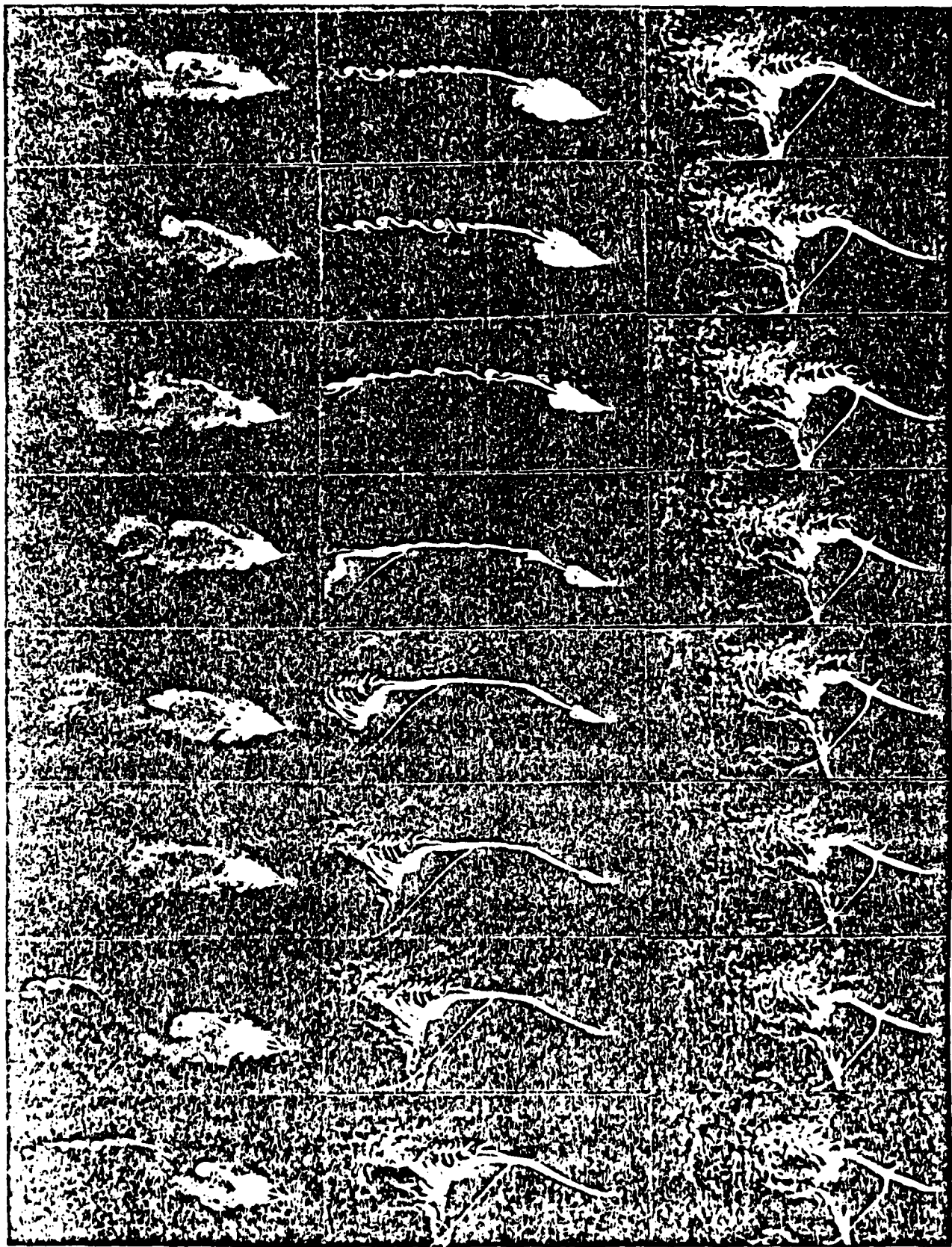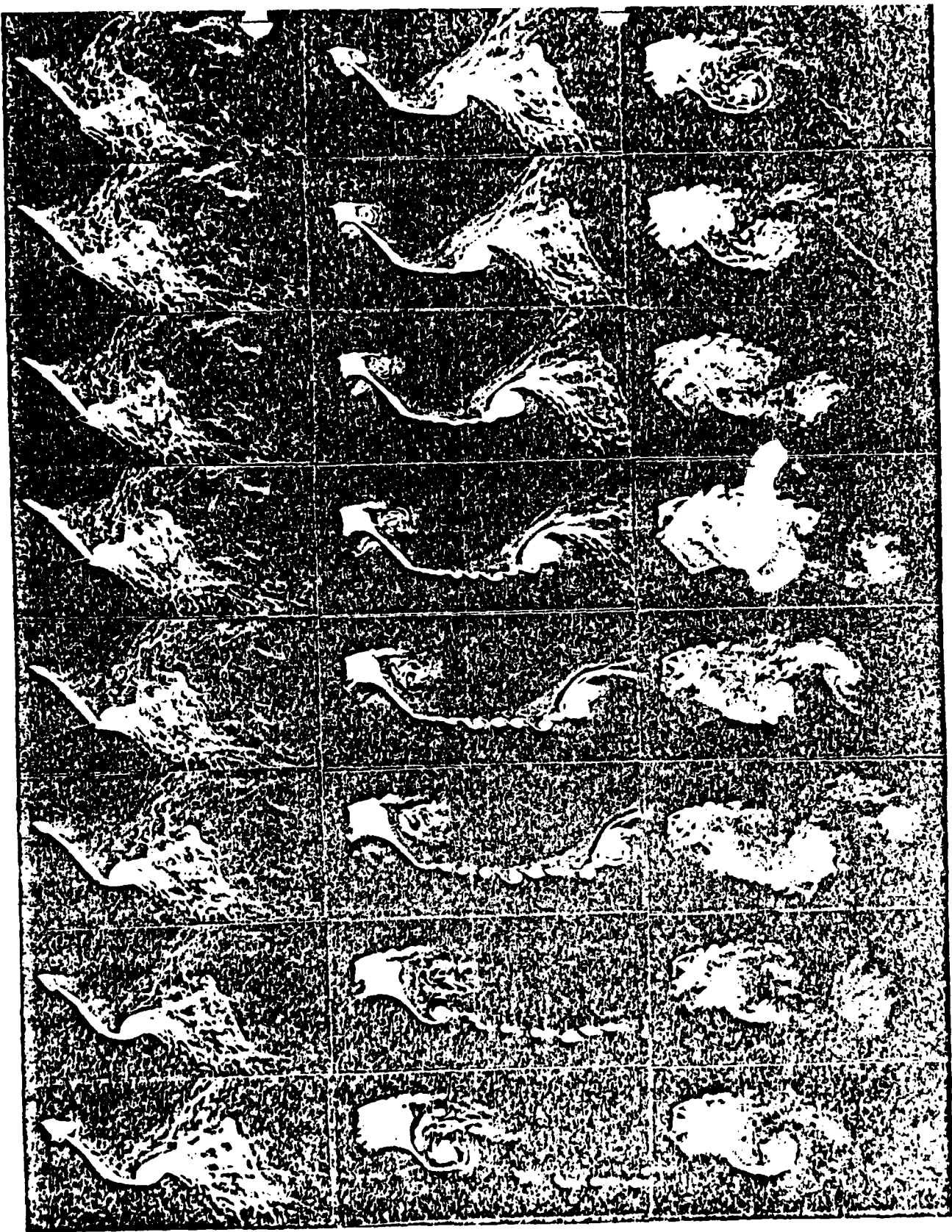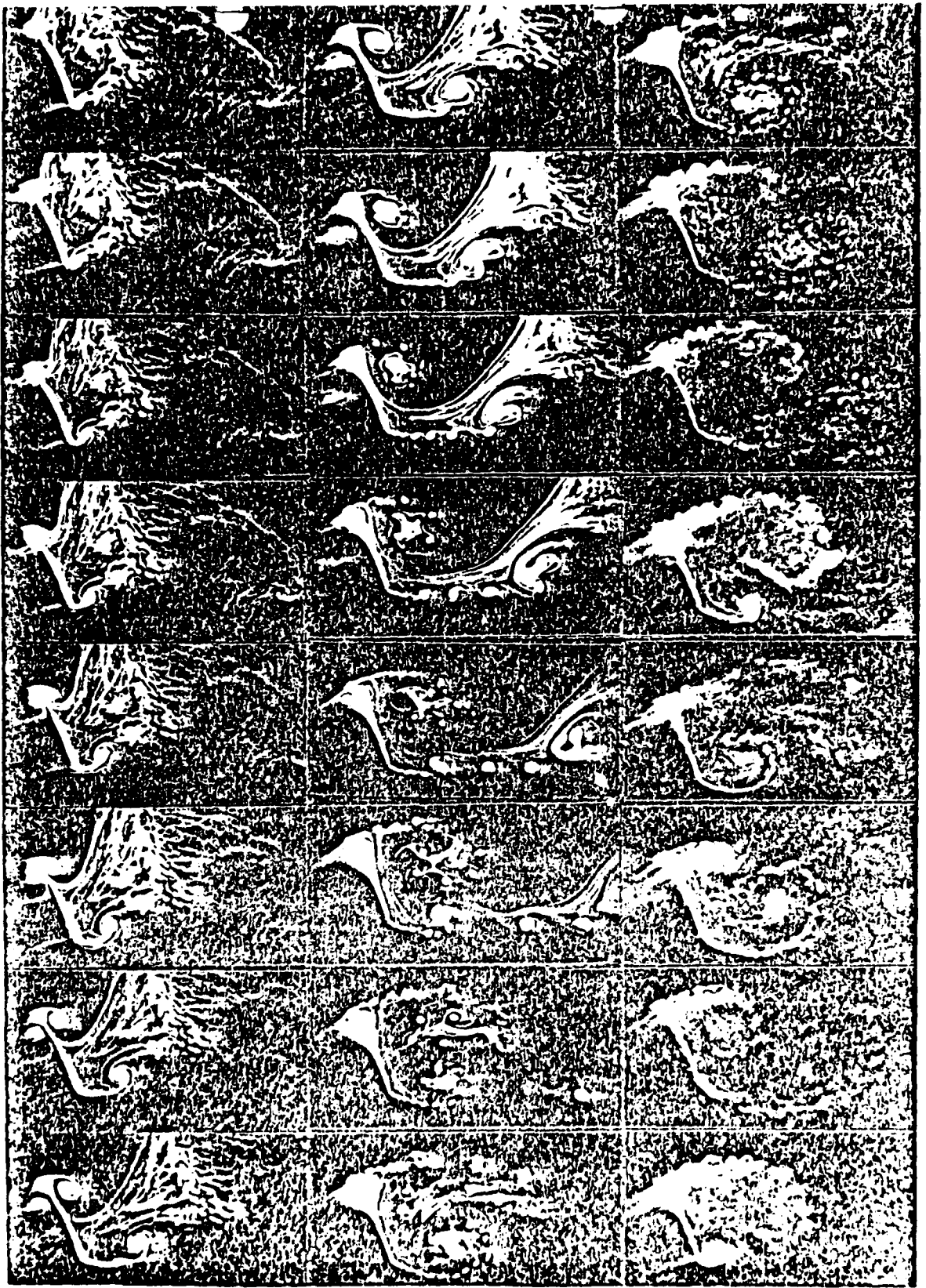
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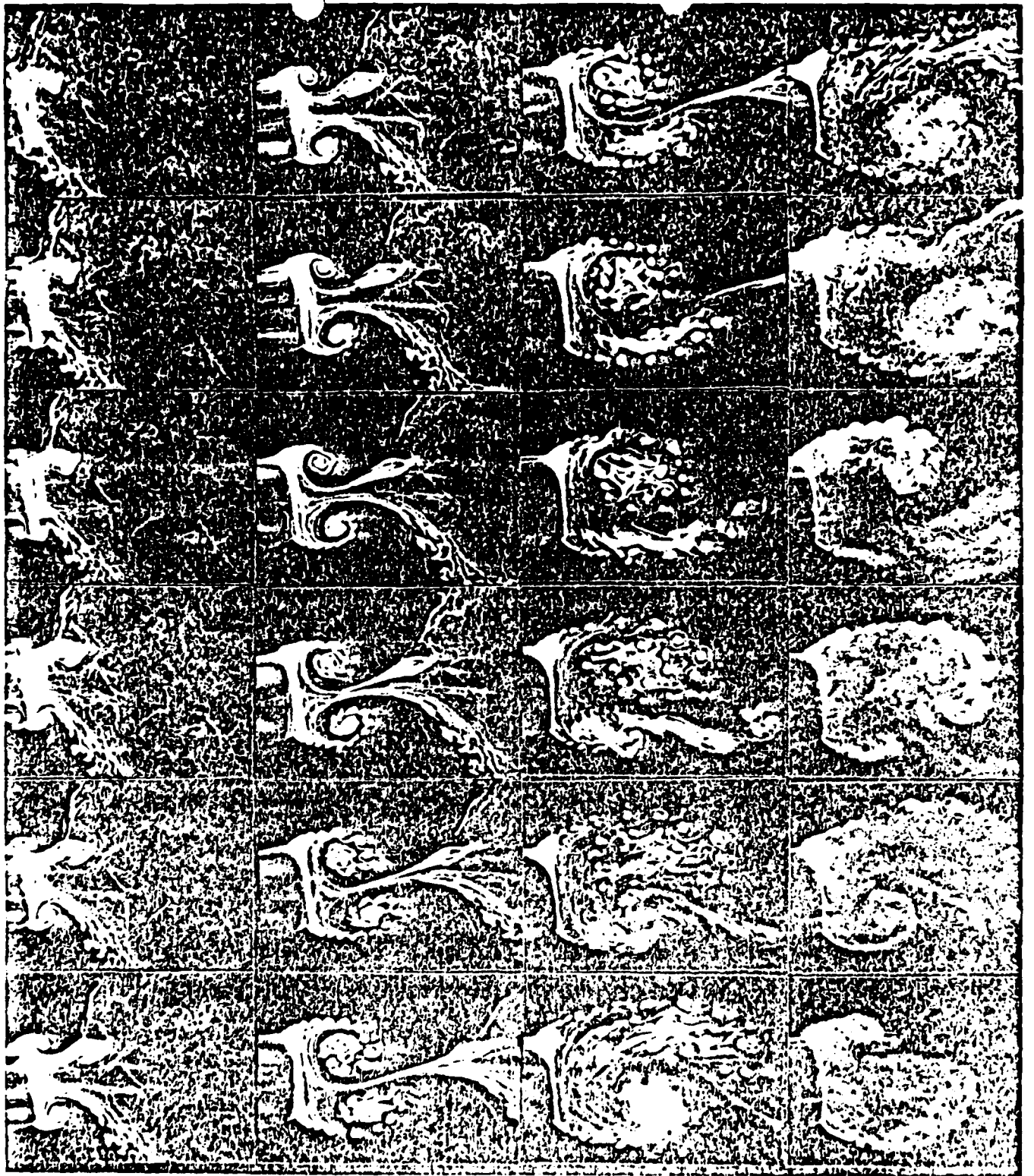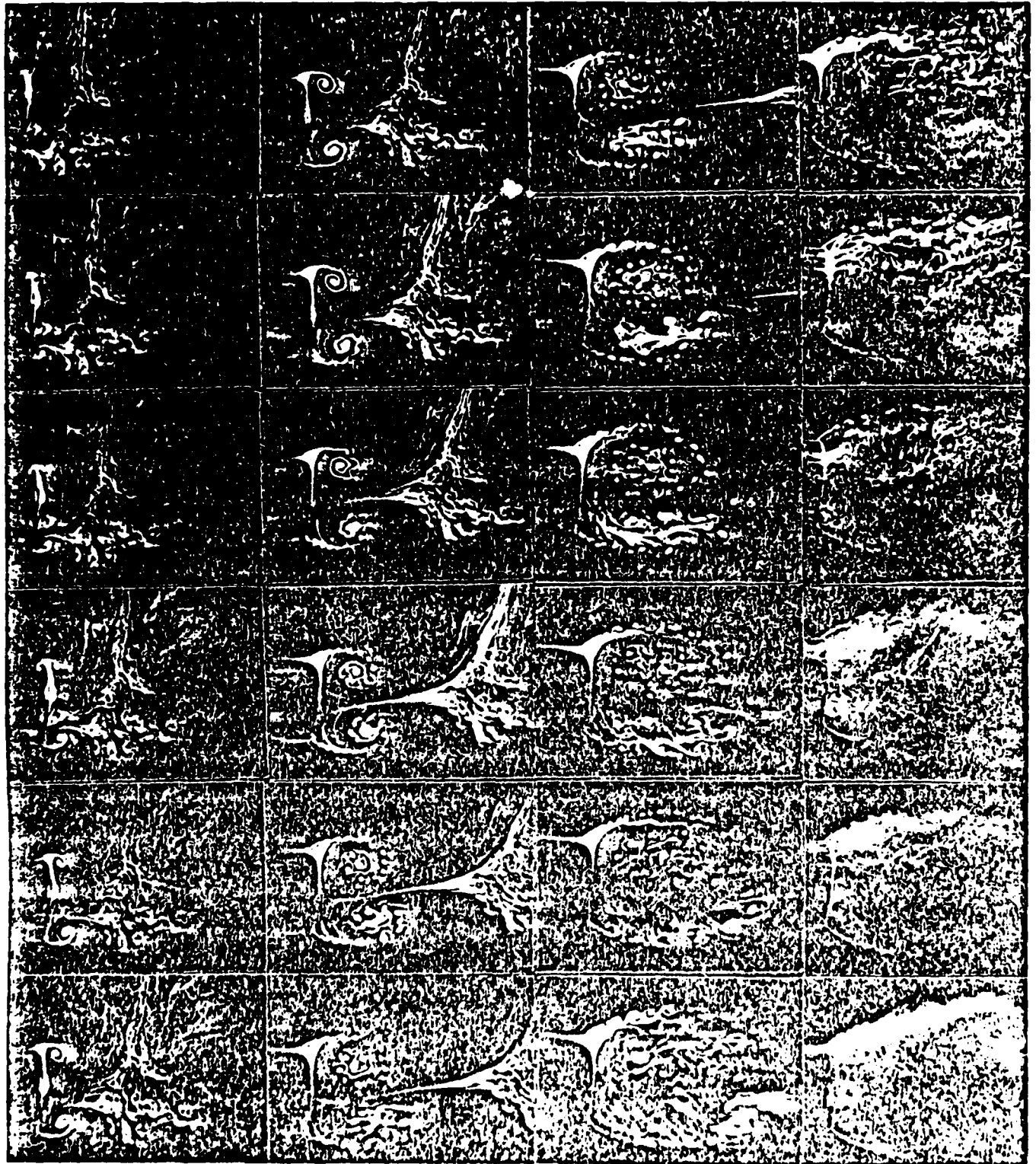
List of Figures

Figure 1. Sequence of accelerating flow around an airfoil for $\alpha = 20^{\circ}$, $\Delta t = 1/16$ sec.

Figure 2. Sequence of accelerating flow around an airfoil for $\alpha = 40^{\circ}$, $\Delta t = 1/16$ sec.

Figure 3. Sequence of accelerating flow around an airfoil for $\alpha = 60^{\circ}$, $\Delta t = 1/16$ sec.

Figure 4. Sequence of accelerating flow around an airfoil for $\alpha = 80^{\circ}$, $\Delta t = 1/16$ sec.

Figure 5. Sequence of accelerating flow around an airfoil for $\alpha = 90^{\circ}$, $\Delta t = 1/16$ sec.

Figure 6. Closeup sequence of vortex formation and decay near the leading edge for $\alpha = 20^{\circ}$, $\Delta t = 1/64$ sec.

Figure 7. Top and center: Single frame photographs taken at $\alpha = 40^{\circ}$. Bottom left: $\alpha = 60^{\circ}$. Bottom right: $\alpha = 80^{\circ}$

Figure 8. Top: Closeup at $\alpha = 80^{\circ}$
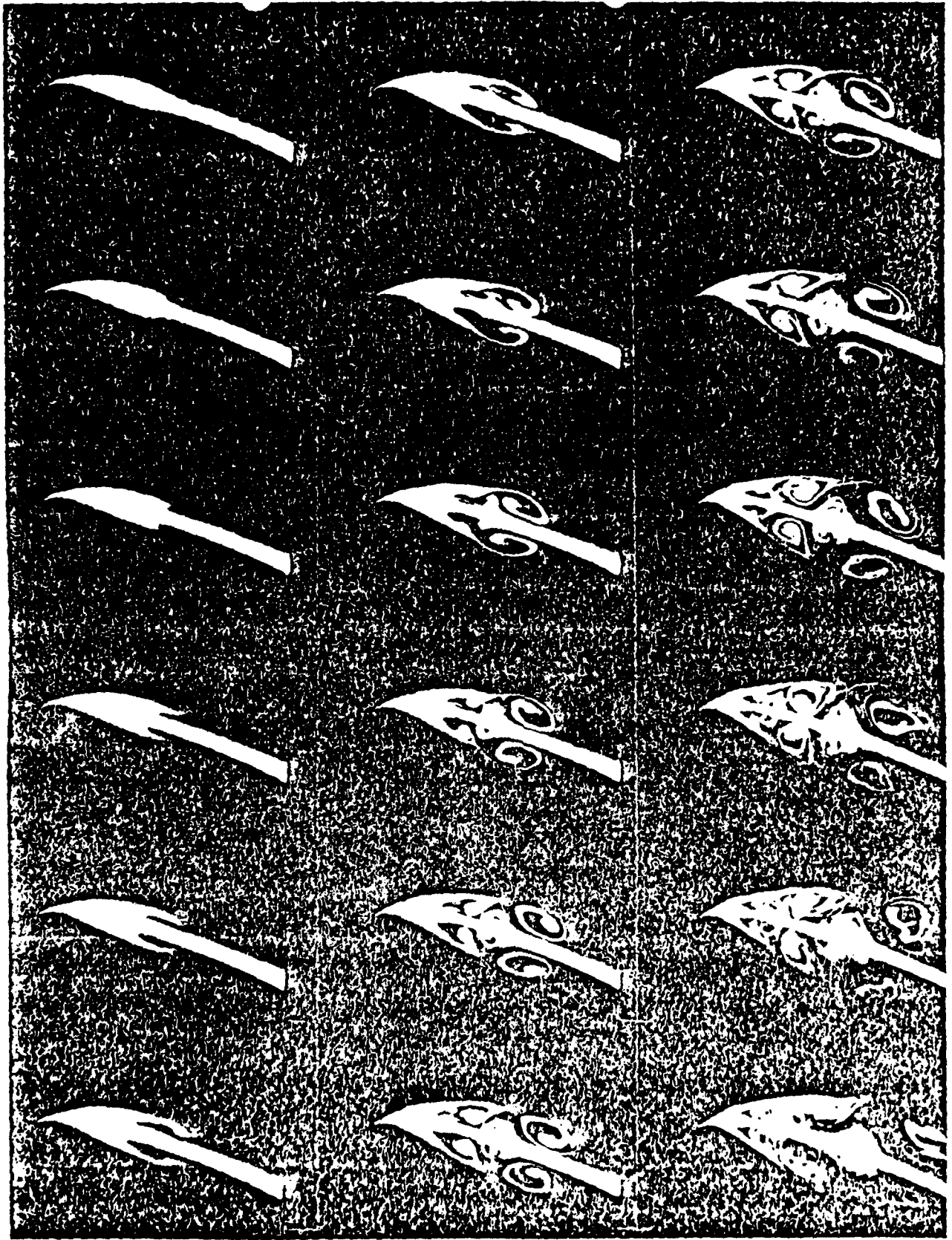Center: $\alpha = 80^{\circ}$
Bottom: $\alpha = 90^{\circ}$