NASA TN D-328

TECHNICAL NOTE

D-328

PHOTOGRAPHIC EVIDENCE OF STREAMWISE ARRAYS OF VORTICES IN BOUNDARY-LAYER FLOW

By Edward J. Hopkins, Stephen J. Keating, Jr.,
and Angelo Bandettini

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON September 1960

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-328

PHOTOGRAPHIC EVIDENCE OF STREAMWISE ARRAYS OF VORTICES IN BOUNDARY-LAYER FLOW

By Edward J. Hopkins, Stephen J. Keating, Jr., and Angelo Bandettini

SUMMARY

Photographs are presented of various models coated with fluorescent oil to show evidence of surface vortices at a Mach number of 3.03. Vortex formation was evidently present on models with forward-facing steps, rearward-facing steps, wires, discrete surface particles, or unswept flat surfaces with sharp leading edges. Some photographs are also presented for the models coated with a sublimation material which clearly indicates the location of boundary-layer transition; however, it does not show the vortices as clearly as the fluorescent oil. The study was made on the models at an angle of attack of 0° at unit Reynolds numbers of 7.7 and 10.7 million per foot. The spacing of the vortices as indicated by the flow studies on the unswept model was smaller at the higher Reynolds number in accordance with Görtler's theory. The flow studies also indicated that stable surface vortices produced by either steps or surface roughness persisted over model areas known to have turbulent boundary layers.

INTRODUCTION

Streamwise vortices in the vicinity of the boundary layer have been studied with considerable interest recently because of the possible connection between the instability of these vortices and the breakdown of a laminar boundary layer into a turbulent boundary layer (e.g., refs. 1 and 2). Streamwise arrays of vortices have been observed by a number of investigators and have been placed in three general classifications: (1) counterrotating arrays predicted by Görtler for viscous flow on a concave surface, (2) co-rotating arrays predicted by Stewart for three-dimensional flow on swept surfaces, and (3) arrays produced by random surface particles, each particle apparently producing a counterrotating pair of vortices. Examples of the first type may be seen in the figures of reference 3 where apparently the necessary concavity of the flow at a Mach number of 2.05 was produced by the separated flow occurring downstream from rearward-facing steps. A number of observers have reported on the occurrence of the second type on rotating discs and on swept wings at both subsonic and supersonic speeds (e.g., ref. 4) while the third type has been studied primarily at subsonic speeds (e.g., ref. 5).

The main purpose of this study was to find evidence of surface vortices by use of the improved visual-flow technique (ref. 6) in which fluorescent oil is viewed under ultraviolet lights. In several cases the measured vortex spacing as indicated by the visual-flow studies is compared with the spacing given by the Görtler theory of reference 7.

NOTATION

d average distance between vortices

h height of step or single element roughness

l length

M Mach number

$\frac{R}{l}$ unit Reynolds number, $\frac{\rho u}{\mu}$ per foot

u velocity

δ boundary-layer thickness taken between $\frac{u}{u_o} = 0$ and 0.9985

μ viscosity coefficient

ρ density

Subscript

o free-stream conditions

APPARATUS AND MODEL DESCRIPTION

Wind Tunnel

The investigation was conducted in an 8-inch supersonic nozzle, in which the Mach number in the test section was 3.03. The stagnation pressure range of the wind tunnel is from 35 to 105 psia.

The average transition Reynolds number was found to be 3.0 million. This number is based on local flow conditions and the transition length at the beginning of transition as determined from tests of a cone with a vertex angle of 20°. No change in the transition Reynolds number was observed throughout a unit Reynolds number range from 7 to 12 million per foot.

Models and Support

The step model was sting-supported, the attachment being on the A367 lower surface to minimize sting interference. The plan form was rectangular with a span of 4 inches and a chord length of 3 inches. Steps located 1 inch from the model leading edge had heights ranging from 0.1 inch for the rearward-facing step to 0.058 inch for the forward-facing step. Various step heights were obtained by attaching flat plates of different thicknesses to the surface immediately downstream of the rearward-facing step. During most of the investigation, end plates were attached to the model to prevent possible interference effects from flow around the tips of the model. However, the flow conditions in the central portion of the model were found to be the same with or without end plates. All parts of the model were ground to a finish of 8 microinches (rms), the finish normally used on cams. A leading-edge thickness of 0.009 inch was employed to reduce effects possibly arising from leading-edge nicks caused by foreign particles in the air stream. A dimensional sketch of the step model is presented in figure 1 and a photograph of this model mounted in the wind tunnel is presented in figure 2.

Limited visual-flow tests were also conducted on the flat surface of a wing model. The wing had a leading-edge sweepback of 48.5° and an aspect ratio of 1.4. The leading-edge thickness was about 0.005 inch and the wing span was 4 inches.

For those tests in which boundary-layer trips were used to produce vortices, either a piano wire for single-element roughness or silicon-carbide particles for distributed roughness were cemented to the model surfaces.

TEST CONDITIONS AND VISUAL-FLOW TECHNIQUES

Wind-Tunnel Test Conditions

All tests were conducted at a Mach number of 3.03 at either a unit Reynolds number of 7.7 or 10.7 million per foot. Free-stream stagnation temperatures ranged from 65° to 85° F. An angle of attack of 0° was maintained throughout the investigation.

Fluorescent-Oil Technique

The fluorescent-oil technique employed was identical to that described in reference 6. A mixture of about 1 part of yellow fluorescent powder and 40 parts of SAE 40 oil was brushed on the model and photographed under ultraviolet light after the flow pattern was established. The light was provided by a single EH-4 ultraviolet lamp located about 8 inches from the model. A time exposure of 5 seconds at f/16 was found to give satisfactory contrast on a panchromatic film with an ASA rating of about 100.

Sublimation Technique

A 3 6 7

The sublimation technique employed was the same as the one described in reference 8. For the present tests approximately 12 coats of a saturated solution of naphthalene and petroleum ether were sprayed on the model. After the petroleum ether had evaporated, and before the model was installed in the wind tunnel, the naphthalene was rubbed smooth with a piece of paper to reduce the possibility of slight roughness causing transition.

RESULTS AND DISCUSSION

In the photographs presented herein the observable striations are believed to be indicative of surface vortices. Similar striations were observed by Ginoux in a sublimable material behind rearward-facing steps as reported in reference 3. Detailed spanwise surveys made by Ginoux, in and downstream of the reattachment region of the flow, with total-head probes indicated strong regularly spaced perturbations in pressure which could not be explained by irregularities in either the model or the air flow upstream of the model. Ginoux suggested, therefore, that these measured perturbations could be explained by the presence of regularly spaced longitudinal vortices.

Figure 3(a) shows striations on the rearward-facing step similar to those found by Ginoux. In figure 3(b) the same regular patterns are defined more clearly by the fluorescent oil. Test conditions were identical and the same spacing of striations is found in both photographs. Both visual-flow techniques also showed striations near the leading edge.

Figure 4 shows enlarged photos of the leading-edge region. The step was filled in and there was less oil on the surface. A comparison of figure 4(a) with figure 4(b) indicates that the vortices were closer together at the higher Reynolds number, a result which is compatible with the theory of reference 7. According to reference 7 the spacing between adjacent Görtler vortices first to form without decaying is given by the following equation:[1]

$$d = 2.5\ \delta \tag{1}$$

where δ is the boundary-layer thickness. At a distance of 0.29 inch from the wing leading edge, approximately the distance at which the striations are first discernible, the vortex spacing was estimated from (1) above, the boundary-layer thickness for $M = 3.03$ being estimated by the method given in reference 9. These estimated and experimental results for the Reynolds numbers of 7.7 and 10.7 million are given in the table below:

A
3
6
7

$R/l \times 10^{-6}$ per foot	d, in.	
	Measured[1]	Estimated
7.7	0.021±0.002	0.017
10.7	0.016±0.002	0.014

[1]Average distance between striations on photographs was assumed to be equal to the average vortex spacing.

The result that the vortices are closer together at the higher Reynolds number is in accord with theory, but the estimated spacings are smaller than the measured spacings.

The sublimation photograph presented in figure 5 does not show clearly the fine striations found near the wing leading edge in the fluorescent-oil photograph but does indicate that laminar flow existed to the wing trailing edge at a Reynolds number of 10.7 million.

Both the forward-facing steps and the rearward-facing step produced vortices which evidently persisted at least to the trailing edge as shown in figures 3 and 6. The equations of reference 9 gave an approximate value for the flow curvature necessary to produce streamwise vortices in the separated region. Computations of flow curvatures based on pressure measurements made on models described in reference 10, geometrically similar to the model of the present investigation, showed that the curvature existing at the separated region on both forward-facing and rearward-facing steps was two orders of magnitude greater than the minimum value required. Thus the curvature required to produce vortices was so slight that this degree of curvature might even exist at the leading edge.

[1]It is recognized that this equation was derived from a theory for incompressible flow and is not strictly applicable to the present investigation.

A wire attached to the smooth step model (h = 0) 1 inch behind the leading edge produced longitudinal vortices as evidenced by figure 7. In this case the concave curvature of flow required for vortex formation would be present both ahead of and behind the wire.

A typical example of the flow pattern produced in fluorescent oil by discrete surface particles attached to a flat wing surface is presented in figure 8(a). To show that the surface vortices produced by the particles persisted over the areas where the boundary layer was turbulent, a sublimation photograph for the same flow conditions as for the fluorescent oil photograph is presented in figure 8(b). To indicate the effect of these surface particles on natural transition, a sublimation photograph is also presented for the model with natural transition in figure 9.

A 3 6 7

CONCLUDING REMARKS

Fluorescent-oil photographs presented show evidence of streamwise vortices being produced at a Mach number of 3.03 on a flat plate with no steps or protuberances, behind a rearward-facing step, behind a forward-facing step, and behind a wire roughness. Evidence is given that for a flat-plate wing with distributed roughness, the vortices persisted over areas known to have a turbulent boundary layer. Moreover, the photographs showed that the vortices were closer together at the higher Reynolds number, a result in accord with Görtler's theory.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., May 11, 1960

REFERENCES

1. Hama, Francis R., Long, James D., and Haggarty, John C.: On Transition From Laminar to Turbulent Flow. Inst. of Fluid Dynamics and Applied Math., Univ. of Maryland, Tech. Note BN-81, 1956.

2. Kovasznay, Leslie S. G.: A New Look at Transition. Durand Centennial Conference on Aeronautics and Astronautics, Stanford University, Aug. 5-8, 1959.

3. Ginoux, Jean J.: Experimental Evidence of Three-Dimensional Perturbations in the Reattachment of a Two-Dimensional Laminar Boundary Layer at M = 2.05. Training Center for Experimental Aerodynamics (Belgium) Tech. Note 1, Nov. 1958.

4. Gregory, N., Stuart, J. T., and Walker, W. S.: On the Stability of Three-Dimensional Boundary Layers With Application to the Flow Due to a Rotating Disk. Philosophical Transactions, Royal Soc. (Brit.) ser. A, vol. 248, no. 943, July 14, 1955, pp. 155-199.

5. Gregory, N., and Walker, W. S.: The Effect on Transition of Isolated Surface Excrescences in the Boundary Layer. British A.R.C., FM 1482, Perf. 698, Oct. 1950.

6. Loving, Donald L., and Katzoff, S.: The Fluorescent-Oil Film Method and Other Techniques for Boundary-Layer Flow Visualization. NASA MEMO 3-17-59L, 1959.

7. Görtler, H.: On the Three-Dimensional Instability of Laminar Boundary Layers on Concave Walls. NACA TM 1375, 1954.

8. Main-Smith, J. D.: Chemical Solids as Diffusible Coating Films for Visual Indication of Boundary-Layer Transition in Air and Water. R. and M. No. 2755, British A.R.C., 1950.

9. Lee, J. D.: The Influence of High Adverse Pressure Gradients on Boundary Layers in Supersonic Flow. Univ. of Toronto, Inst. of Aerophysics, Rep. 21, Oct. 1952.

10. Chapman, Dean R., Kuehn, Donald M., and Larson, Howard K.: Investigation of Separated Flows in Supersonic and Subsonic Streams With Emphasis on the Effect of Transition. NACA TN 3869, 1957.

A
3
6
7

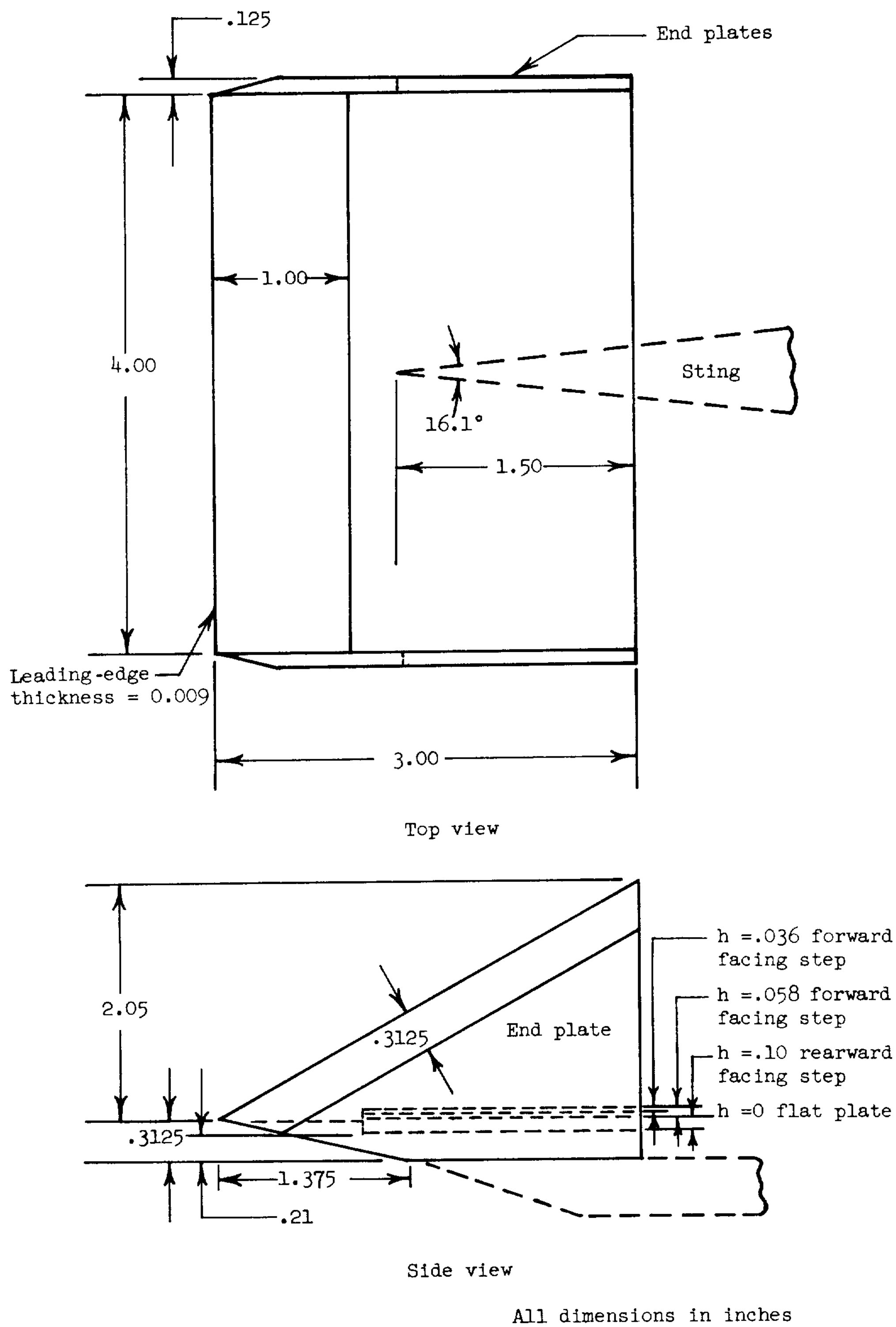
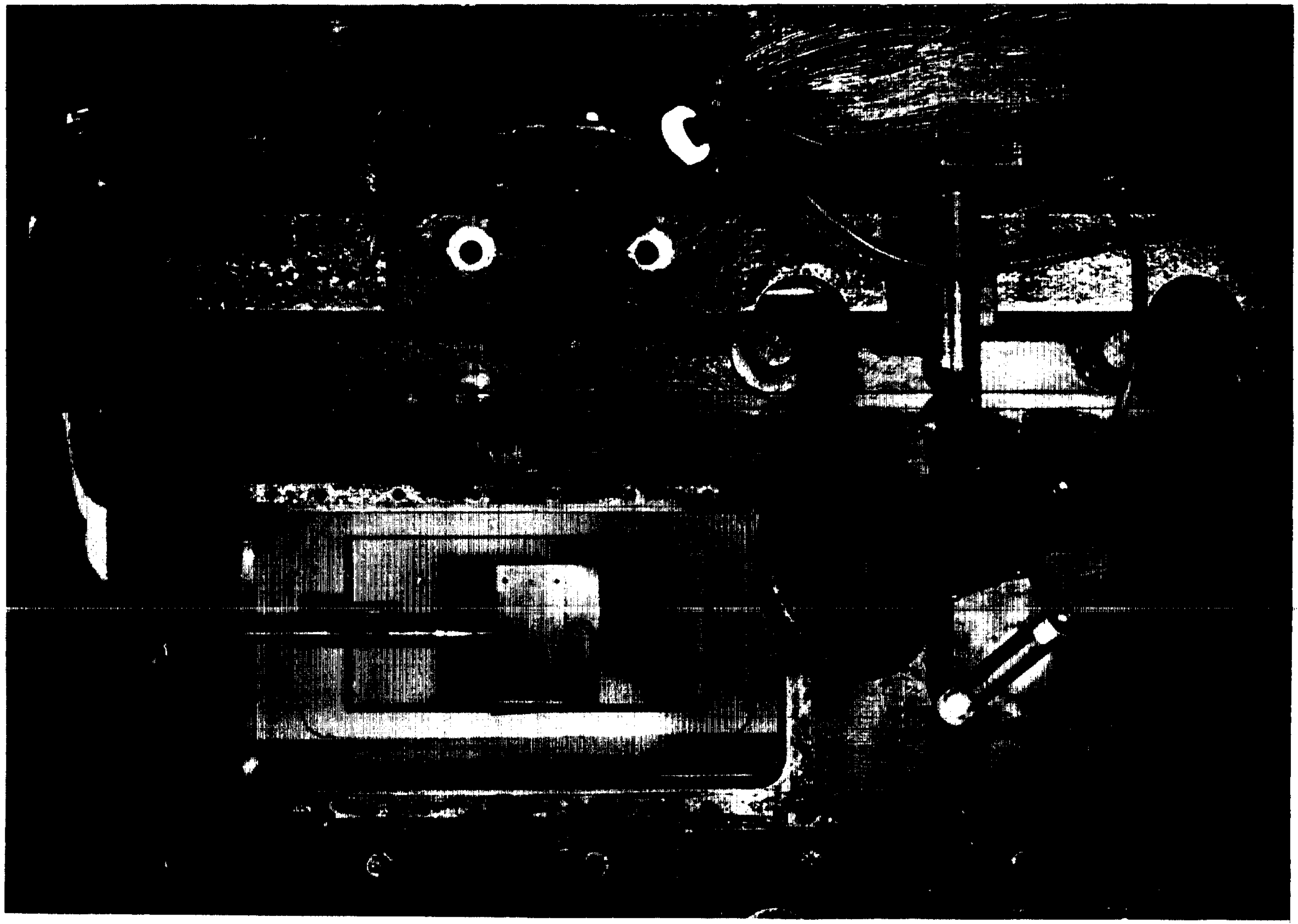


Figure 1.- Dimensional sketch of step model.

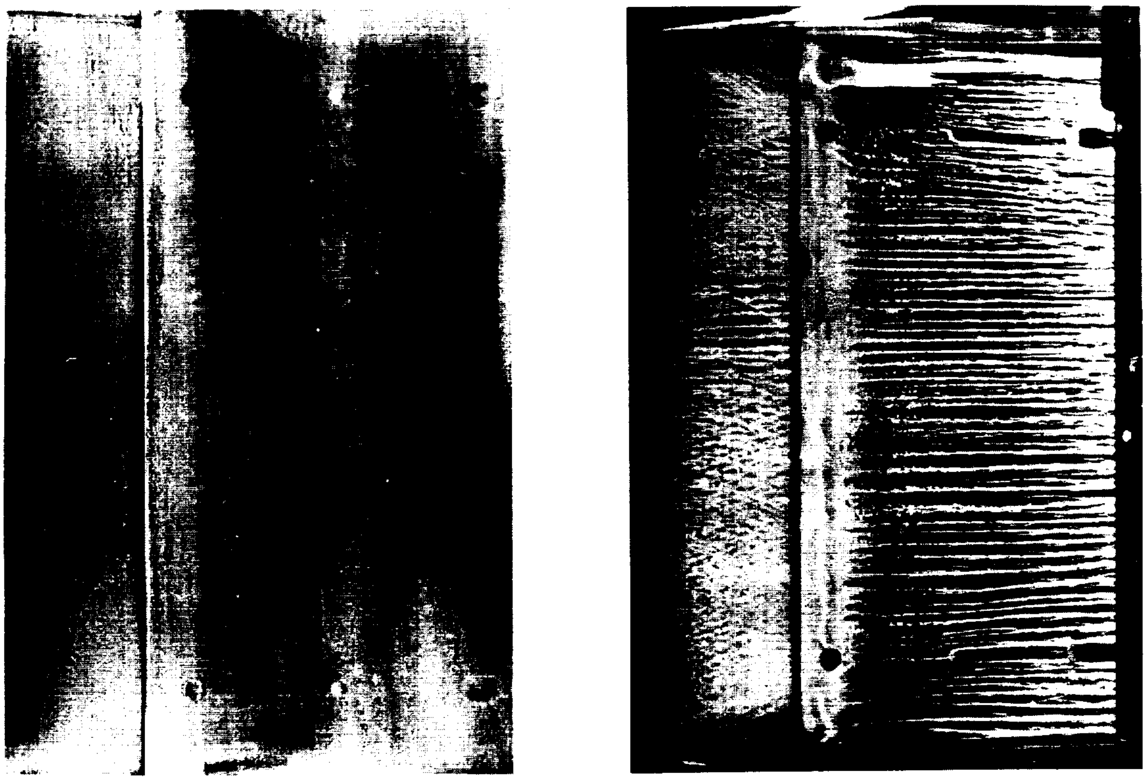


A-26288

Figure 2.- Step model mounted in the 8-inch supersonic nozzle test apparatus.

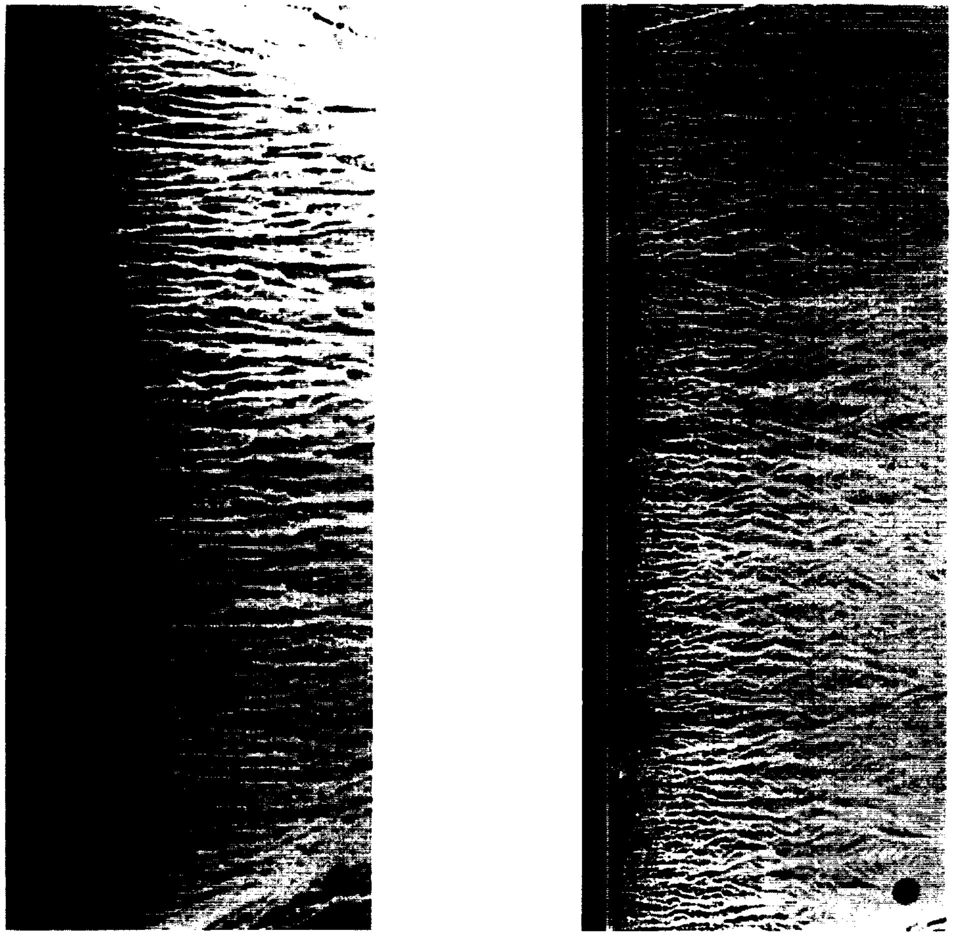
A
3
6
7

A
3
6
7



(a) Naphthalene. (b) Fluorescent oil.

Figure 3.- Rearward-facing step model; h = 0.10 inch, $R/l = 7.7 \times 10^6$ per foot.



(a) $R/l = 7.7\times10^6$ per foot.

(b) $R/l = 10.7\times10^6$ per foot.

Figure 4.- Smooth-step model (h = 0) coated with fluorescent oil.

A
3
6
7

A
3
6
7

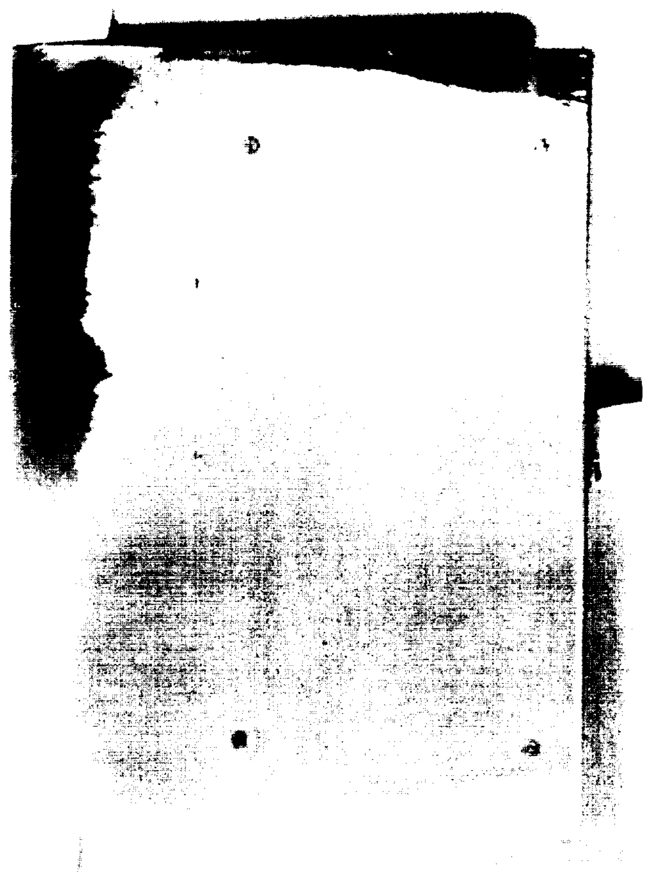
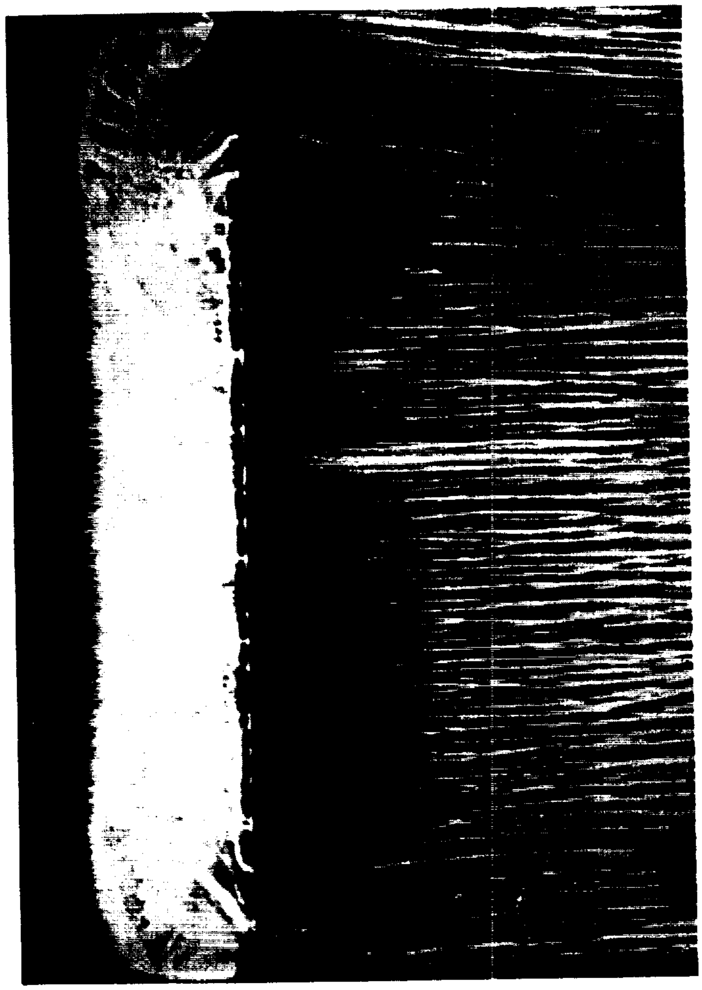


Figure 5.- Smooth-step model (h = 0) coated with napthalene; $R/l = 10.7 \times 10^6$ per foot.

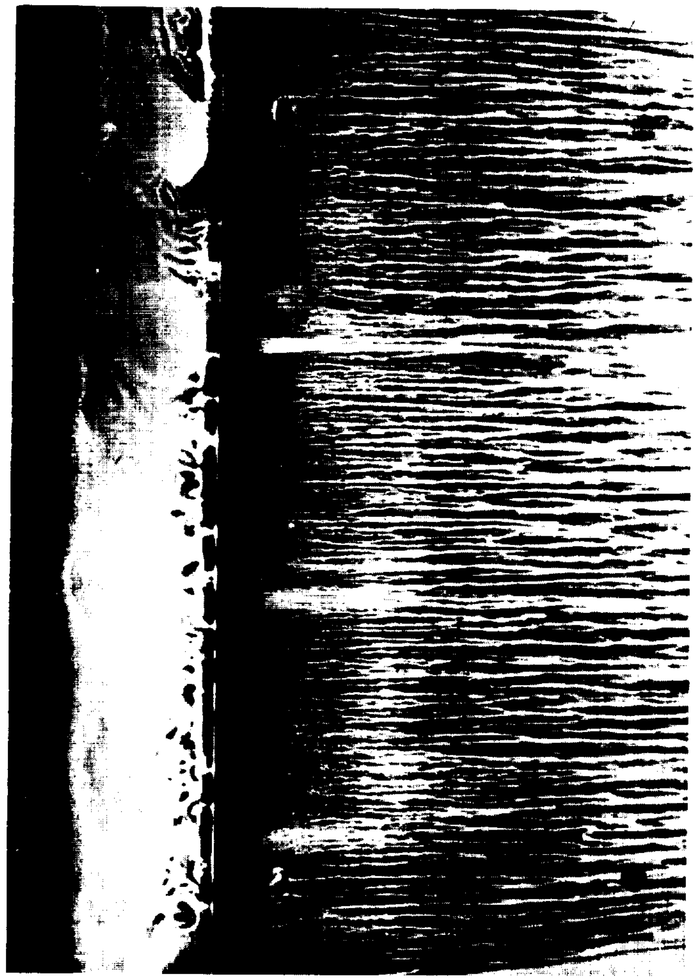


(c) $R/l = 7.7\times10^6$ per foot; h = 0.036 inch.

Figure 6.- Continued.

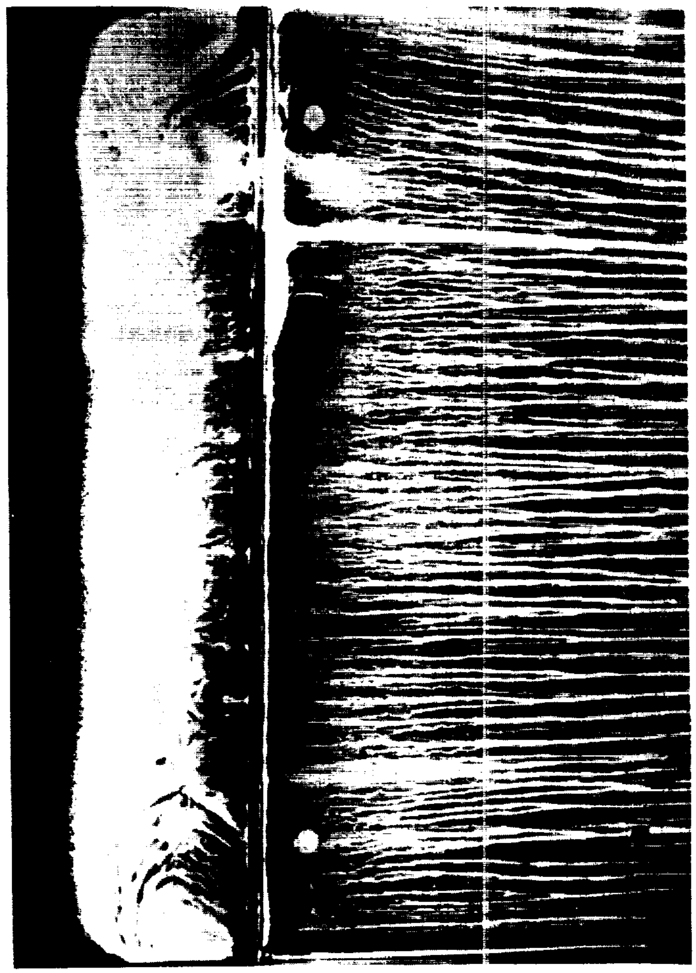
A
3
6
7

A
3
5
7



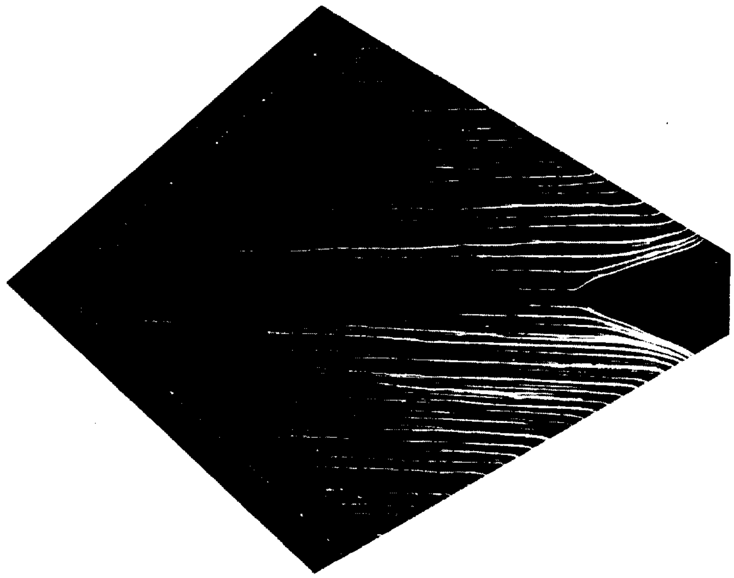
(d) $R/l = 10.7 \times 10^6$ per foot; h = 0.036 inch.

Figure 6.- Concluded.

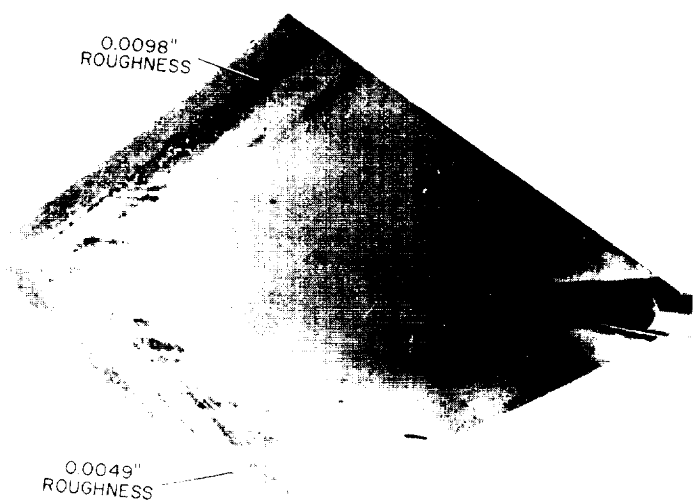


A
3
6
7

Figure 7.- Smooth-step model (h = 0) with fluorescent-oil coating and wire; h = 0.051 inch, $R/l = 7.7\times10^6$ per foot.



(a) Fluorescent oil.



(b) Sublimation.

Figure 8.- Flat-plate wing with distributed roughness particles located 1/4-inch from the leading edge; $R/l = 7.7 \times 10^6$ per foot, sweepback = 48.5°, aspect ratio = 1.4.

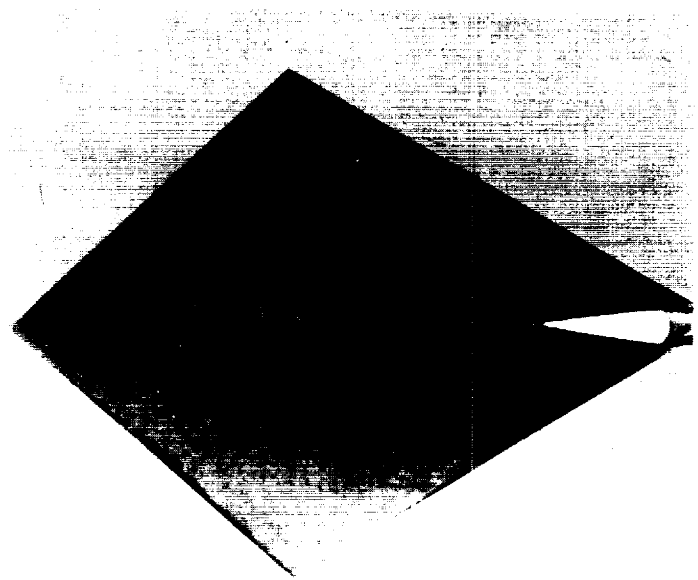


Figure 9.- Flat-plate wing with natural transition indicated by naphthalene; $R/l = 7.7 \times 10^6$ per foot, sweepback = 18.5°, aspect ratio = 1.4.

A
3
6
7

NASA TN D-328
National Aeronautics and Space Administration.
PHOTOGRAPHIC EVIDENCE OF STREAMWISE ARRAYS OF VORTICES IN BOUNDARY-LAYER FLOW. Edward J. Hopkins, Stephen J. Keating, Jr., and Angelo Bandettini. September 1960. 20p. OTS price, $0.50. (NASA TECHNICAL NOTE D-328)

Photographs are presented of various models coated with fluorescent oil to show evidence of surface vortices at a Mach number of 3.03. Vortex formation was evidently present on models with forward-facing steps, rearward-facing steps, wires, discrete surface particles, or unswept flat surfaces with sharp leading edges. Some photographs are also presented for the models coated with a sublimation material which clearly indicates the location of boundary-layer transition; however, it does not show the vortices as clearly as the fluorescent oil.

Copies obtainable from NASA, Washington (over)

I. Hopkins, Edward J.
II. Keating, Stephen J., Jr.
III. Bandettini, Angelo
IV. NASA TN D-328

NASA

NASA TN D-328
National Aeronautics and Space Administration.
PHOTOGRAPHIC EVIDENCE OF STREAMWISE ARRAYS OF VORTICES IN BOUNDARY-LAYER FLOW. Edward J. Hopkins, Stephen J. Keating, Jr., and Angelo Bandettini. September 1960. 20p. OTS price, $0.50. (NASA TECHNICAL NOTE D-328)

Photographs are presented of various models coated with fluorescent oil to show evidence of surface vortices at a Mach number of 3.03. Vortex formation was evidently present on models with forward-facing steps, rearward-facing steps, wires, discrete surface particles, or unswept flat surfaces with sharp leading edges. Some photographs are also presented for the models coated with a sublimation material which clearly indicates the location of boundary-layer transition; however, it does not show the vortices as clearly as the fluorescent oil.

Copies obtainable from NASA, Washington (over)

I. Hopkins, Edward J.
II. Keating, Stephen J., Jr.
III. Bandettini, Angelo
IV. NASA TN D-328

NASA

NASA TN D-328
National Aeronautics and Space Administration.
PHOTOGRAPHIC EVIDENCE OF STREAMWISE ARRAYS OF VORTICES IN BOUNDARY-LAYER FLOW. Edward J. Hopkins, Stephen J. Keating, Jr., and Angelo Bandettini. September 1960. 20p. OTS price, $0.50. (NASA TECHNICAL NOTE D-328)

Photographs are presented of various models coated with fluorescent oil to show evidence of surface vortices at a Mach number of 3.03. Vortex formation was evidently present on models with forward-facing steps, rearward-facing steps, wires, discrete surface particles, or unswept flat surfaces with sharp leading edges. Some photographs are also presented for the models coated with a sublimation material which clearly indicates the location of boundary-layer transition; however, it does not show the vortices as clearly as the fluorescent oil.

Copies obtainable from NASA, Washington (over)

I. Hopkins, Edward J.
II. Keating, Stephen J., Jr.
III. Bandettini, Angelo
IV. NASA TN D-328

NASA

NASA TN D-328
National Aeronautics and Space Administration.
PHOTOGRAPHIC EVIDENCE OF STREAMWISE ARRAYS OF VORTICES IN BOUNDARY-LAYER FLOW. Edward J. Hopkins, Stephen J. Keating, Jr., and Angelo Bandettini. September 1960. 20p. OTS price, $0.50. (NASA TECHNICAL NOTE D-328)

Photographs are presented of various models coated with fluorescent oil to show evidence of surface vortices at a Mach number of 3.03. Vortex formation was evidently present on models with forward-facing steps, rearward-facing steps, wires, discrete surface particles, or unswept flat surfaces with sharp leading edges. Some photographs are also presented for the models coated with a sublimation material which clearly indicates the location of boundary-layer transition; however, it does not show the vortices as clearly as the fluorescent oil.

Copies obtainable from NASA, Washington (over)

I. Hopkins, Edward J.
II. Keating, Stephen J., Jr.
III. Bandettini, Angelo
IV. NASA TN D-328

NASA

NASA TN D-328

(Initial NASA distribution: 1, Aerodynamics, aircraft; 2, Aerodynamics, missiles and space vehicles; 20, Fluid mechanics.)

Copies obtainable from NASA, Washington

NASA

NASA TN D-328

(Initial NASA distribution: 1, Aerodynamics, aircraft; 2, Aerodynamics, missiles and space vehicles; 20, Fluid mechanics.)

Copies obtainable from NASA, Washington

NASA

NASA TN D-328

(Initial NASA distribution: 1, Aerodynamics, aircraft; 2, Aerodynamics, missiles and space vehicles; 20, Fluid mechanics.)

Copies obtainable from NASA, Washington

NASA

NASA TN D-328

(Initial NASA distribution: 1, Aerodynamics, aircraft; 2, Aerodynamics, missiles and space vehicles; 20, Fluid mechanics.)

Copies obtainable from NASA, Washington

NASA