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**QUALITATIVE RESPONSES OF A VORTEX CORE  
TO  
TIP BLOWING AND INTERSECTING AIRFOILS**

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## FOREWORD

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## ABSTRACT

This investigation deals with the qualitative responses of a trailing vortex core to changes in its convective velocity produced in two different ways, (a) by injection of air into the vortex core and (b) by the flow field of a lifting surface in the path of the core. Flow pictures of the vortex core and vorticity measurements in the core show that an axial momentum injection of approximately 35% of the total wing drag alters the vortex structure and behavior quite drastically by effectively inducing a more rapid dispersion of the vorticity in the core. The data indicates that the phenomenon is governed by the rate of injection of the momentum rather than the mass flow rate as reported recently by Rinehart<sup>1</sup>. There also seems to be an optimum rate of injection beyond which increased injection does not bring about equally significant changes in the vortex core. Flow patterns of the region of interaction between the flow field of a lifting surface and the vortex core show two modes of vortex response; (a) the vortex core bends, following the streamline shape until it intercepts the wake of the wing where it is abruptly dispersed, or (b) the vortex core may be sliced into two smaller vortices when the vortex hits the leading edge of the wing.

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# NOMENCLATURE

|                |                                                                                                                       |
|----------------|-----------------------------------------------------------------------------------------------------------------------|
| A              | Aspect ratio of the wing                                                                                              |
| $A_i$          | Cross-sectional area of the injection port ( $\text{in}^2$ )                                                          |
| c              | Chord of the wing (in)                                                                                                |
| $C_L$          | Lift coefficient of the wing                                                                                          |
| $C_l$          | Section lift coefficient                                                                                              |
| $\bar{d}$      | Distance downstream of the wing trailing edge (in)                                                                    |
| d              | Distance downstream of the wing trailing edge/chord of the wing                                                       |
| $\bar{D}$      | Induced drag of the wing                                                                                              |
| D              | Total drag of the wing                                                                                                |
| $\ell$         | Distance of the vortex core centre from the horizontal plane through the leading edge of the intersecting wing (in)   |
| M              | Rate of axial momentum injection into the vortex core ( $\rho A_i U_i^2$ )                                            |
| $r_c$          | Radius of the vortex core (in)                                                                                        |
| S              | Half-span of the wing (in)                                                                                            |
| $\bar{t}$      | Thickness of the wing section (in)                                                                                    |
| t              | Age of the vortex core (sec)                                                                                          |
| $U_\infty$     | Free-stream velocity (ft/sec)                                                                                         |
| $U_i$          | Velocity of injection (ft/sec)                                                                                        |
| X              | Rate of mass flow injection ( $\rho A_i U_i$ )                                                                        |
| $\alpha$       | Axial momentum injection rate/total drag of the wing<br>( $\rho A_i U_i^2 / D$ ) - injection parameter                |
| $\bar{\alpha}$ | Axial momentum injection rate/ $\rho \Gamma^2$                                                                        |
| $\beta$        | Mass flow injection parameter - $XU_\infty / \rho \Gamma^2$                                                           |
| $\gamma$       | Ratio of the distance of the axis of the vortex from the wing leading edge to the vortex core radius ( $\ell / r_c$ ) |

|                |                                                                                                                              |
|----------------|------------------------------------------------------------------------------------------------------------------------------|
| $\bar{\delta}$ | Ratio of the vortex core radius to the chord of the interacting wing ( $r_c/C_w$ )                                           |
| $\delta$       | Ratio of the vortex core radius to the thickness of the intersecting wing ( $r_c/\bar{t}_w$ )                                |
| $\theta$       | Angle of attack of the wing (degrees)                                                                                        |
| $\rho$         | Density                                                                                                                      |
| $\Gamma$       | Theoretical circulation around the trailing vortex assuming elliptic loading of the wing                                     |
| $\Omega$       | Peak vorticity in the core                                                                                                   |
| $\Omega_a$     | Vorticity in the core averaged over a minute                                                                                 |
| $\lambda$      | Ratio of effective frontal projection of the wing to the vortex core radius ( $\approx [0.06 + .013\theta_w]/\bar{\delta}$ ) |
| $\eta$         | Efficiency of the vorticity meter - ratio of the indicated vorticity to the true vorticity                                   |

#### Subscripts

- o refers to the case of no injection
- i refers to the case with tip injection
- g refers to the vortex-generating wing
- $\omega$  refers to the intersecting wing

## 1. INTRODUCTION

Trailing vortices left behind lifting surfaces, as a result of the roll-up of the vorticity shed from these surfaces, have received a great deal of investigation recently (e.g., Refs. 2 and 3). The structure and behavior of this tip vortex is closely dependent on the convective velocity of the core because of the strong coupling between the axial and swirling velocities in all swirling flows. This study investigates how the vortex characteristics can be altered significantly by altering this convective velocity by some means.

The presence of a lifting surface in the path of a trailing vortex core can induce a change in the vortex as well as alter the aerodynamic forces and moments acting on the lifting surface. This vortex-lifting surface interaction is of particular importance in the aerodynamics of the helicopter rotors. For the same loading, helicopter rotor blades tend to produce relatively stronger tip vortices than conventional aircraft wings because the tip sections of the rotor blades are usually more heavily loaded. Moreover, the vortices instead of streaming away from the source as in the case of fixed wing aircraft interact with the following blades of the same rotor or in a multiple-rotor configuration, with the blades of the other rotor, the degree of interaction depending on the flight configuration. This interaction occurring inevitably in one flight configuration or other, causes a strong repeated impulse loading on the rotor blades with consequent severe loading, vibrational, and operational fatigue problems in the rotor. In addition, it creates a loud characteristic slapping noise<sup>4</sup>.

In view of the above operational problems of the rotor blades, it is very desirable to reduce the intensity of the tip vortices, as it is the intensity of the core that is responsible for the severity of these problems. Since the circulation around the core of a trailing vortex is directly related to the lift of the airfoil, the most desirable way of reducing the intensity of these concentrated vortex cores is to disperse the vorticity over a larger region. In other words, one would like to increase the core size or the "age" of these vortices.

In conventional, fixed-wing aircraft, the problems associated with the

tip vortices originate from the remarkable persistence of these vortices, as is evident to anyone who has managed to look up at the contrails behind a high-flying jet aircraft on a clear day. These constitute a hazard to any small aircraft attempting to fly, takeoff, or land in the immediate wake of a bigger aircraft. With the advent of ever bigger aircraft like the Boeing 747 and the Lockheed C-5A, this danger is constantly increasing. Any practical method of dispersing the concentrated vorticity in such vortex cores would help in alleviating the problems of air traffic control at busy airports as it would permit closer intervals between landings and takeoffs.

Although in practice, viscosity does spread out vorticity, it is a rather slow process as is evident from the persistence of these tip vortices. A fast process like vortex breakdown, capable of abruptly spreading out vorticity over a larger region and causing transition to large-scale turbulence and the consequent rapid diffusion of vorticity, is desirable. Breakdown results from decelerating a supercritical vortex<sup>5</sup>, but no method of supplying the necessary deceleration has yet been successfully exploited. An alternate method of reducing the intensity of these vortices would be a modification right at the source, such as the modification of the wing-tip configuration or loading distribution on the wing by proper design. Various attempts in this direction have been partially successful<sup>6</sup>, but a performance penalty is inevitably incurred. A delay in effect of the roll-up process by a spanwise fence of small lateral extent placed at the tip of the wing approximately near the point where the vortex takes off can achieve similar results but roll-up being a rapid and dominant process, appreciable alteration is rather difficult<sup>7</sup>.

This opens up the question whether it is possible to alter beneficially these trailing vortices by aerodynamic means without the disadvantages mentioned earlier. A possible method seems to be an axial flow injection into the core. An attempt at analyzing such a method has been published by Rinehart<sup>1</sup>. However, he has attempted an analysis in terms of possible changes in the steady state solution of the Navier-Stokes Equations. We feel that the major effect is more likely to be changes in the stability of the flow. Trailing vortices are wakes and as such are usually associated with an axial velocity defect. The spreading

of the wake involves a radial inflow near the axis. From studies of confined vortices<sup>8</sup>, it is known that vortices with radial inflow are much more stable than those with a radial outflow. This suggests that injection at the tip of an airfoil could destabilize the trailing vortex and expedite the vorticity diffusion. One object of this investigation is a preliminary study of the feasibility of such a method by exploring the changes in vortex structure induced by blowing. The method is particularly attractive for helicopters since the injection mass flow is readily available due to the centrifugal pumping action of the rotation of the blades. For a jet aircraft, a part of the required thrust could be supplied by engines mounted near the wing tips to provide a convenient source of injection flow.

The interaction of a vortex with a lifting surface is of intrinsic importance in helicopters. The present study deals with the inverse problem of the influence of the changes in the convective velocity induced by the pressure field around the lifting surface on the structure of the vortex. The solution of this inverse problem is required for a better understanding of the interaction problem. The range of validity of the usual method of treating the modification in the loading on lifting surfaces in the proximity of vortices by assuming that the vortex itself remains intact<sup>9</sup> can be explored. In this study, the interaction region was subjected to a systematic qualitative investigation using smoke to visualize the vortex, and the influence of various parameters on the possible modes of interaction was examined.

The investigation was mainly qualitative as accurate measurements of flow quantities in swirling flow without employing highly sophisticated methods are rather difficult. The photographs of the flow patterns in the regions of interest are the main source of information in the determination of the qualitative responses of the vortex core. The interpretation of the photographs is supported by a few measurements with a vorticity meter.

## 2. EXPERIMENTAL SETUP

The tests were conducted in the 7-1/2 ft x 10 ft Wright Brothers Subsonic Wind Tunnel at M.I.T. The tip vortex under study was produced by a 7.75 in. x 31.5 in. rectangular wing (with a symmetrical NACA 0012 profile)

mounted vertically on the floor of the wind tunnel. The wing could be raised or lowered so that the vertical position of the vortex could be changed. The angle of attack of the wing could be varied suitably. The wing had a standard tip, a half-body of revolution of 0012 profile. In addition, there was provision for introducing smoke at the wing-tip for visualizing the tip vortex. The details of the smoke generation arrangement are shown in Fig. 1. Oil under pressure passes through the inner tube and during passage gets heated and vaporized. As it emerges from the wing-tip it condenses to form smoke. This smoke from the tip gets entrained into the vortex thus providing an excellent means of visualizing the vortex. The smoke particles arrange themselves in a characteristic tube-like concentration in the vortex (see Fig. 2) believed to be due to the balance between the centrifugal force field of the vortex and the radial inflow into the vortex. The radius of the tube appears to indicate roughly the size of the viscous core of the vortex.

The wing had provisions for injecting air at the wing tip (Fig. 1). The exit diameter of the injection tube could be reduced from 1/4 in. to 1/8 in. The source of the injection air was a 120 psi reservoir supplied by a reciprocating air pump. The airflow was first passed through a flow meter, a pressure gage recording the pressure of the passing flow at the inlet of the meter. This reading was necessary to calculate the mass flow through the meter. The small capacity of the reservoir and the need to maintain a steady airflow for a considerable period with the rapidly-exhausting reservoir formed an upper bound on the maximum airflow that could be injected into the vortex and effectively prevented the tests from being conducted at higher free stream velocities. The position of the tip of the injection tube was adjusted so that the injection was approximately at the center of the vortex core.

The vortex streaming out of the wing tip was photographed with a Hasselblad camera mounted looking sideways, the position of the camera was adjusted suitably depending on the section of the vortex to be photographed. A black screen mounted on the side wall of the wind tunnel facing the camera provided a good background for the photographs. The screen had a horizontal grid of parallel equidistant lines 2 inches apart in order to provide a rough indication of the size of the vortex. Instantaneous photographs of the flow

were taken because of the random movement of the trailing vortex in the lateral direction, with the amplitude of the oscillation dependent on the distance downstream of the generating wing. Two suitably-placed microflash units served as the light sources. The technique was to darken the wind tunnel completely, keep the aperture of the camera open and flash the flash units simultaneously before closing the aperture.

To supplement the qualitative interpretations of the smoke photographs of the vortex by a simple measurement indicative of the influence of injection, vorticity measurements were made in the vortex core using a standard vorticity meter. Any quantitative measurements in a trailing vortex in a wind tunnel are severely hampered by the random movements of the vortex core around its mean position due to ambient disturbances. Any technique for velocity or vorticity measurements in the core must take this factor into consideration. At present no simple technique for accurate measurements in a vortex far downstream of the source is available. The problem is not so severe very close to the trailing edge of the wing because of the small movements of the vortex close to the wing and most of the measurements reported in the literature<sup>7,10,11</sup> have exploited this aspect quite successfully. However, the far downstream field is of considerable interest and any adequate technique for accurate measurements there is likely to be quite sophisticated (techniques like laser anemometry are being examined by several people). The present investigation is mainly concerned with simple data indicative of the vorticity dispersion in the vortex core or, in other words, the "age" of the vortex core. The decrease in the peak vorticity in a vortex core may be used as a rough indication of the increase in this age of the vortex [for simple laminar viscous diffusion of vorticity, initially concentrated in a line vortex, the ratio of the peak vorticities at any two instants of time is inversely proportional to the ratio of the times (or ages),  $\Omega_2/\Omega_1 = t_1/t_2$  (Ref. 12)]. So it was decided to limit the vorticity measurements to the determination of the peak vorticity in the core. The technique adopted was to position the vorticity meter approximately in the center of the vortex core, using smoke to visualize the vortex and determining over a sufficiently long period the maximum instantaneous rotation speed of the vorticity meter with the aid of the output of the meter displayed on an oscilloscope. These measurements were also supplemented by determining over a

sufficiently long period the maximum possible number of revolutions in 1/10 sec using an electronic counter. The rotation speed of the meter averaged over a minute was also recorded to obtain a rough idea of the movement of the vortex core.

The influence of the pressure field of a lifting surface in the path of the vortex, on the vortex core was investigated by a qualitative examination of the interaction region of the tip vortex with a wing. Interacting wings of three different sizes were tested in order to assess the influence of the relative size of the vortex to the wing size. The wings were all rectangular with NACA 0012 profiles and standard tips. They were mounted on wind tunnel trunnions such that they projected out horizontally like a cantilever (Figs. 3 and 4). The angles of attack of these wings could be varied from  $-10^\circ$  to  $+30^\circ$ . In addition to the side view of the interaction region, the plan view was also photographed. The technique used was the same as in the previous case.

### 3. EXPERIMENTS

#### 3.1 Tip Blowing

The qualitative response of the vortex to the changes in the convective velocity produced by injection at the wing tip was investigated at various injection rates. The angle of attack of the wing was kept constant at  $8^\circ$ , but the experiments were conducted at two different free-stream velocities (44 fps and 88 fps). As it was desired to find out whether the momentum rate of injection or the mass flow rate is the governing factor in the phenomenon, the tests were also conducted at two different exit diameters (1/4 in. and 1/8 in.) of the injection tube.

For each configuration mentioned above, vorticity measurements were made at three different downstream positions (1c, 3c, and 13c downstream of the wing trailing edge). The vortex photographs included the photographs of the upstream (up to  $\sim 10c$  downstream from the trailing edge), (7c to 15c) downstream and far downstream (30c to 45c) sections of the vortex. Close-up views of the vortex near the tip were also taken in some cases using a telephoto lens. The photographs and measurements were repeated for different injection rates. The mass flow rate of injection was measured in each case by the flow meter and was

used to compute the rate of injection of the momentum. At high rates of injection, the injection tip was choked. To eliminate doubts about the true representation of the vortex by the smoke, and to ensure that the flow patterns are not a function of the amount of injected smoke, the experiments were repeated for a single configuration (1/4" nozzle (#1), 44 fps) at each injection rate but for different amounts of smoke injection. The essential similarity of the flow patterns as seen in Fig. 5a and 5b indicates the minor influence of the amount of smoke on the appearance of the vortex core in the photographs.

The important quantities in the problem of the response of a vortex generated by a given wing at a given angle of attack to the changes in the convective velocity produced by injection at the tip are:

- $U_{\infty}$  = Free-stream velocity
- $X$  = Injection mass flow rate
- $M$  = Injection momentum flow rate, and
- $\rho$  = Density

If the wing is assumed to be elliptically loaded, then  $\Gamma = 4SU_{\infty}(C_L/\pi A)$  is the theoretical circulation around the trailing vortices and  $U_{\infty}$  can be replaced by  $\Gamma$  as one of the variables. Two nondimensional parameters can be formed from these quantities.

- a) Characteristic momentum injection parameter  $\equiv \bar{\alpha} = M/\rho\Gamma^2$ .  $\rho\Gamma^2$  is indicative of the induced drag of the wing. But since at high  $C_L$  values, the induced drag dominates (as is true in takeoff and landing configurations in an aircraft) and since it is this regime which is of interest, little qualitative change can be expected by the use of the injection parameter  $\alpha = M/D$  instead of  $\bar{\alpha}$ , where  $D$  is the total drag of the wing. The data will be presented in terms of  $\alpha$ .
- b) The characteristic mass flow injection parameter  $\equiv \beta = XU_{\infty}/\rho\Gamma^2$ . The results, however, show that the vortex response is essentially the same with a smaller nozzle at smaller mass flow rates but at almost the same momentum injection rate, thus indicating that the phenomenon is momentum-rate governed and not mass-flow rate-governed

as reported in Ref. 1. So  $\alpha$  is the governing parameter.

The resulting data consisted of a series of photographs of the vortex and vorticity measurements for different injection rates at each configuration mentioned above.

### 3.2 Intersecting Airfoil

For the investigation of the vortex response to the pressure field of a lifting surface, the tests were conducted at a fixed free-stream velocity (88 fps) but for two angles of attack of the generating wing ( $2^\circ$  and  $8^\circ$ ) corresponding to two different vortex strengths. The angles of attack of the interacting wings were also varied from  $-10^\circ$  to  $20^\circ$  in steps of 10 degrees. For each of the above configurations, photographs of the interaction flow region were taken for different distances of the vortex from the wing leading edge. Note that the vortex core was at right angles to the span of the wing (oblique interaction should exhibit essentially the same qualitative features).

In this problem of the vortex response to the changes in the vortex core due to changes in the convective velocity produced by an intersecting wing, the important quantities are:

1.  $\theta_g$  - Angle of attack of the generating wing (indicative of the vortex strength)
2.  $\theta_w$  - Angle of attack of the interacting wing (indicative of increased frontal area of interaction)
3.  $\delta$  - Ratio of vortex core radius to the wing thickness
4.  $\gamma$  - Ratio of the distance of the axis of the vortex from the interacting wing to the vortex core radius.

The effective frontal dimension of the interacting wing is approximately

$$C_w \left[ \frac{\bar{t}_w}{2C_w} + 0.7 \frac{\pi}{180} \theta_w \right] .$$

Therefore, the important parameters are  $\theta_g$ ,  $\gamma$ , and

$$\frac{C_\omega}{r_c} \left[ \frac{\bar{t}_\omega}{2C_\omega} + \frac{2.2}{180} \theta_\omega \right] ;$$

i.e.,  $\theta_g$ , and  $\lambda = (1/\delta) (0.06 + 0.013\theta_\omega)$  because  $\bar{t}_\omega/C_\omega = .12$  for all interacting wings. For  $\gamma \sim 0$ ,  $\theta_g$  and  $\lambda$  are the only parameters.

#### 4. DISCUSSION OF RESULTS

##### 4.1 Tip Blowing

###### 4.1.1 Flow Patterns

Figures 6 through 14 show the upstream, downstream and far downstream sections of the vortex core for increasing values of  $\alpha$ . Figure 15 shows the close-up view of the vortex close to the wing trailing edge with and without blowing. It can be seen that up to  $\alpha \approx 0.2$  (Figs. 6 through 8), tip blowing has not appreciably altered the appearance and behavior of the vortex core far downstream although there do exist some local changes immediately downstream of the injection point. Changes can be seen at  $\alpha \approx 0.30$  (Fig. 9), and at  $\alpha = 0.4$  (Fig. 10) the changes in the vortex characteristics are very profound. A further increase in blowing above  $\alpha \approx 0.4$  does not exhibit further substantial changes in the qualitative response of the vortex core (Figs. 11 through 14). The vortex is not at all visible far downstream above  $\alpha = 0.6$  (Figs. 12 through 14), but this may be due to the inadequacy of the amount of smoke introduced rather than the complete effective dispersion of vorticity. The same qualitative behavior of the vortex seen upstream can be observed far downstream also by introducing proper amounts of smoke. A semblance of a weak core does exist far downstream at values of  $\alpha$  as high as 0.6 (Fig. 11) in spite of the spectacular "dissipative" appearance of the vortex upstream.

The familiar discrete-eddy-like appearance of the edge of the core at sufficiently high values of  $\alpha$  seems to indicate that the profound changes in the vortex produced by tip blowing are probably stability-oriented. But any further definitive conclusion has to come from a detailed investigation into the mechanism. The use of two nozzle configurations (No. 1  $\sim 1/4"$ , No. 2  $\sim 1/8"$ ) and free-stream velocities (44 and 88 fps) permitted  $\alpha$  and  $\beta$  to be varied independently. Figure 16a shows a series of flow patterns at similar values of

$\alpha$  but for different values of  $\beta$ . On the other hand Fig. 16b exhibits considerable changes in the core for the same values of  $\beta$  (1.46), but different values of  $\alpha$  (0.1 and .35). From Figs. 16 a and b, it seems fair to conclude that the phenomenon is momentum-rate dominated, rather than mass-flow-rate dominated.

#### 4.1.2 Vorticity Measurements

Figure 17 shows the effect of blowing on the peak vorticity in the vortex core at 1, 3, and 13c downstream of the wing trailing edge, for both the nozzles at both speeds (except in the 1c case). The peak vorticity appears to increase initially with blowing before dropping back to the original value at  $\alpha \sim 0.2$  and then steadily decreases to around 50% of the original value at  $\alpha \approx .35$ .

The initial increase in Fig. 17 could lead to the conclusion that small amounts of injection cause more vorticity to get rolled up into the tip vortex. This does not seem to be correct. The effect can apparently be attributed to two operating characteristics of the vorticity meter: 1) The vorticity meter is a mechanical instrument with a relatively slow response time and does not indicate the instantaneous vorticity but rather averages it out over a small time and space domain. As the vorticity is spread out permitting the meter to see the vorticity for a longer time, it may indicate an increase in peak vorticity even though it is actually reduced by the spreading. 2) The efficiency of the meter as defined by the ratio of the indicated vorticity to the true vorticity is critically dependent (Fig. 18) on the axial velocity of the flow in which the meter is placed. An increase in the axial velocity results in a considerable increase in the meter efficiency ( $\eta$ ) especially at the low velocities at which present experiments were conducted (higher speeds demand higher injection rates for equal changes in the vortex response and the upper bound was dictated by the injection source capacity). Injection can increase the axial velocity sensed by the meter considerably leading to increased  $\eta$  and higher peak vorticity readings. If such is indeed the case, one would expect that the measurements reporting such an increase would be most severe for smaller nozzle (#2) at lower speed (44 fps) and the least severe for the larger nozzle (#1) at higher speed (88 fps) at the same downstream position of the meter. Figure 17 shows that this is indeed so. Also, one would expect that the increase in vorticity because

of the effective increase in efficiency of the meter brought about by the increased effective axial velocity due to blowing would be less severe at larger distances downstream of the wing. Figure 17 also indicates that such is indeed the case, although the results at 13c downstream distance are more difficult to interpret and less meaningful because of the larger lateral movement of the vortex there.

Hence, the vorticity measurements made are difficult to interpret in the region  $\alpha = 0$  to  $0.2$ , although one is tempted to conclude that blowing has almost negligible effect on the vortex in this range as evidenced by the photographs of the vortex core. Any definitive statement would require a more accurate technique of measurement at far higher free-stream velocities where the increase in efficiency of the meter due to effective increase in axial velocity will be negligible.

The peak vorticity begins to decrease at  $\alpha = 0.2$  and drops to  $\approx 50\%$  of the original value at  $\alpha = 0.35$ . Above  $\alpha = 0.2$ , the measurements show a consistency which is remarkable considering the crudeness of the measurements and the wide range of parameters varied. Increases in  $\alpha$  beyond  $\sim 0.5$  bring relatively little further decreases in the peak vorticity. Figure 17 shows this levelling off quite clearly. Again as before, the measurements at 13c downstream show a relatively large amount of scatter due to the vortex movement, but the qualitative behavior is essentially the same. The excellent correlation of data with  $\alpha$  above  $\alpha \sim 0.2$  confirms the fact that the governing parameter is  $\alpha$ .

Figure 19 shows the ratio of average vorticities with and without blowing plotted against  $\alpha$ . The results are, however, difficult to interpret because of the various unknown factors involved in the averaging process, but the qualitative behavior is essentially the same as in the case of peak vorticity measurements. The increase in average vorticity at low values of  $\alpha$  is much smaller than that in peak vorticity seen in Fig. 17. It even completely disappears in the averaged values far downstream (Fig. 19c). This tends to confirm the speculation that this initial increase is entirely spurious.

Finally, the conclusions drawn from the flow pictures are consistent with those drawn from the vorticity measurements.

## 4.2 Intersecting Airfoil

We will now deal with the vortex response to changes in the convective velocity produced by the flow field of interacting lifting surfaces. As one can expect, as long as the vortex core passes at a relatively large distance from the wing ( $\gamma > 1$ ), it remains relatively unaffected (Figs. 20 through 22). As the core is brought closer to the wing (Figs. 23, 24) ( $\gamma \approx 1$ ), although the core remains unchanged in the immediate vicinity of the wing, it gets disrupted rather abruptly when it intercepts the wake of the wing. The closer the vortex core is to the wing, the closer this disruption point is to the wing trailing edge. Of course, if the vortex intercepts the separated region over a stalled wing (Figs. 25, 26), the disruption takes place over the wing near the leading edge. There is very little upstream influence of any disturbances in the vortex core ahead of the point of sharp disruption, apparently due to the supercritical nature of the vortex core. The disruption mode often looks very much like vortex breakdown (Figs. 23 and 24).

When the vortex core is close to the wing, it bends laterally over the wing (Figs. 21 through 23, 27 and 28) due to the image effect of the wing surface. As can be expected, this effect is large for small values of  $\delta$  (Figs. 21 and 22).

For small values of  $\gamma$  ( $\sim 1$ ), the interaction depends on the relative size of the frontal projection of the wing to the size of the vortex core ( $\lambda$ ). For small values of  $\lambda$ , the disturbance is localized, but the vortex seems to be rather less inclined to bend around and gets disorganized somewhat (Fig. 27) whereas it easily assumes the shape of the streamline at that point and bends around smoothly for larger values of  $\lambda$  (Figs. 23 and 24). In general, for large values of  $\gamma$ , changes in  $\lambda$  do not seem to appreciably alter the basic behavior of the core (Figs. 20 and 21).

When the vortex hits the leading edge of the wing ( $\gamma \sim 0$ ) (Figs. 26, 28 through 37), it either bends around quite sharply before eventual disruption further downstream (Figs. 26, 28 through 34), or it gets sliced into two smaller vortices (Figs. 35 through 37) which follow the two different surfaces of the wing before eventual disruption. The former mode of interaction occurs for higher values of  $\lambda$  and  $\theta_g$  while the latter seems to occur for lower values

of  $\lambda$  and  $\theta_g$ . When the vortex gets split, the two resulting vortices have the same sense of rotation as is depicted rather beautifully by the image effect of the wing surfaces inducing opposite drifts over the top and bottom surfaces (Fig. 37b). Figure 38 shows approximately the regions in which each mode of interaction can be expected.

## 5. CONCLUSIONS

1. The smoke pictures of the tip vortex and the rough vorticity measurements in the vortex indicate that tip blowing can indeed serve as an effective aerodynamic means of spreading out the vorticity in concentrated vortex cores such as trailing vortices.
2. The experimental data seems to correlate well with the momentum rate of injection thus indicating that it is the momentum rate of injection that is decisive in determining the response of the vortex core to injection and not the rate of mass flow injection as was reported recently in a theoretical investigation<sup>1</sup>.
3. There seems to be an optimum injection rate beyond which further blowing is of little advantage. This optimum rate corresponds to an axial momentum injection rate of approximately 35% of the total wing drag ( $\alpha \sim .35$ ).
4. Two modes of vortex response to an intersecting airfoil are identified.
  - a) The vortex core bends, following the streamline shape until it intercepts the wake of the wing, at which point it is abruptly dispersed.
  - b) When the vortex hits the leading edge of the wing ( $\gamma \sim 0$ ), it may get sliced into two smaller vortices rotating in the same direction but following the two different surfaces of the wing.

Concentrated vortex cores are very sensitive to the changes in the convective velocity. The changes produced by the interaction of the vortex core with a wing shown herein should lead to a better understanding of the

vortex-rotor blade interaction in helicopters. The changes produced by tip blowing in the vortex core are promising. Although  $\alpha = .35$  seems to be a rather high value, the mere fact that tip blowing can beneficially spread out the vorticity in a vortex and affect its behavior is quite encouraging. However, a complete understanding of the phenomenon needs a reasonably thorough theoretical explanation and a more accurate and detailed experimental investigation, culminating probably in a systems-evaluation of the concept of blowing.

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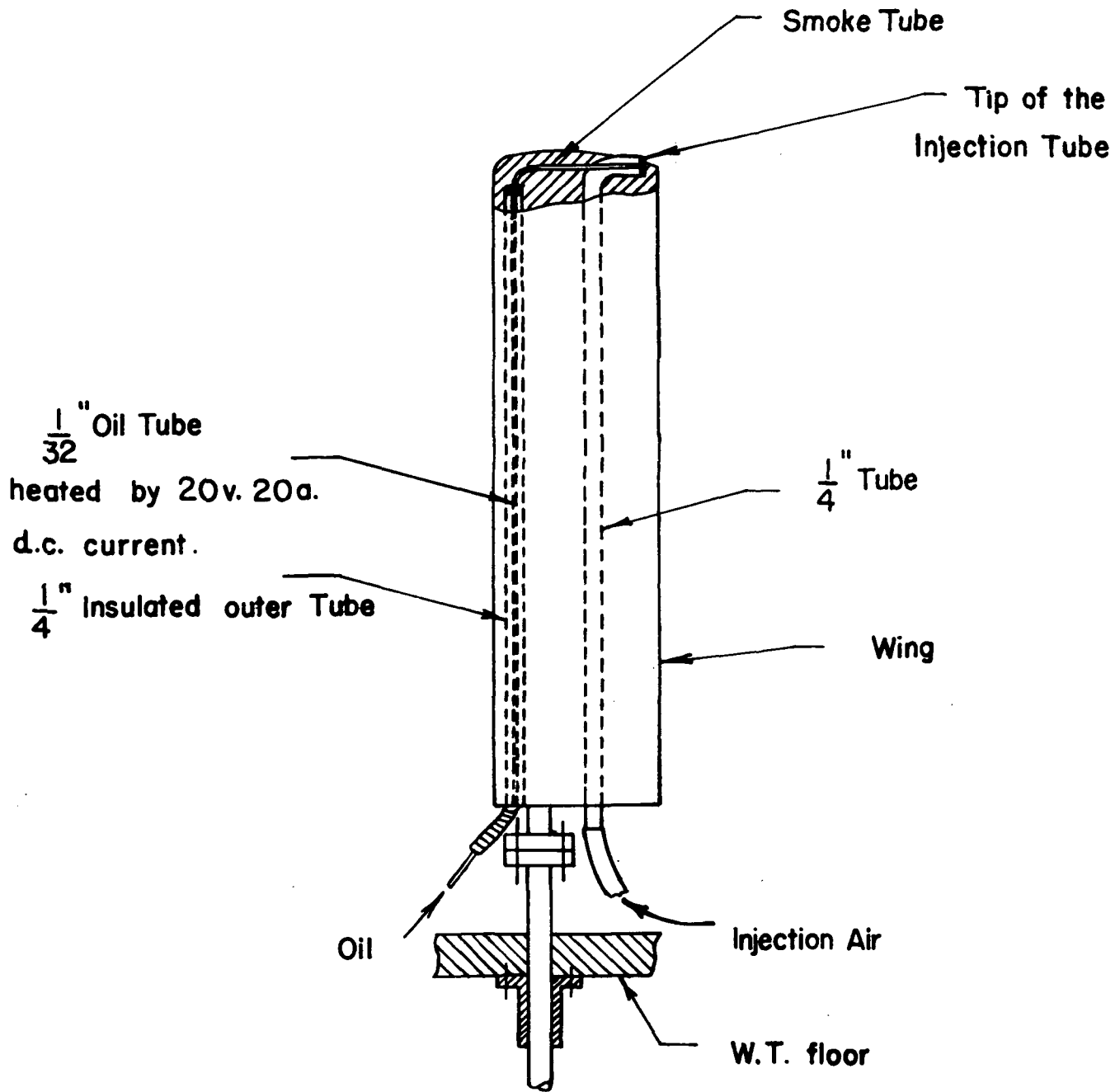


FIG. 1 SKETCH OF THE GENERATING WING SHOWING ARRANGEMENTS  
FOR INTRODUCING SMOKE AND BLOWING AT THE TIP

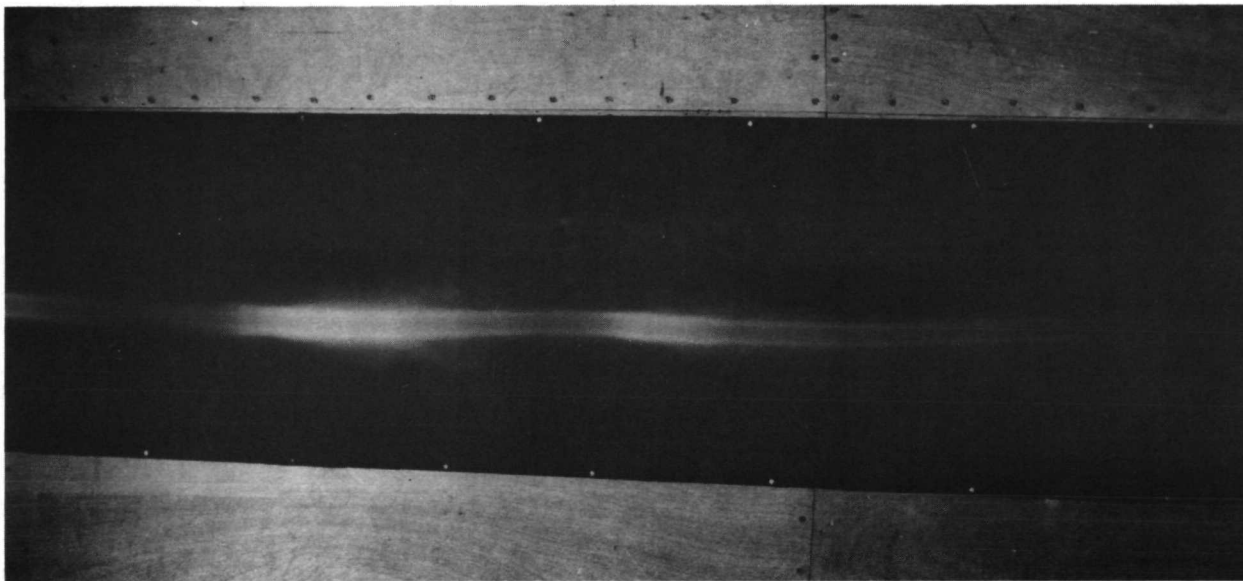


FIG. 2 TYPICAL SMOKE VISUALIZATION OF THE VORTEX

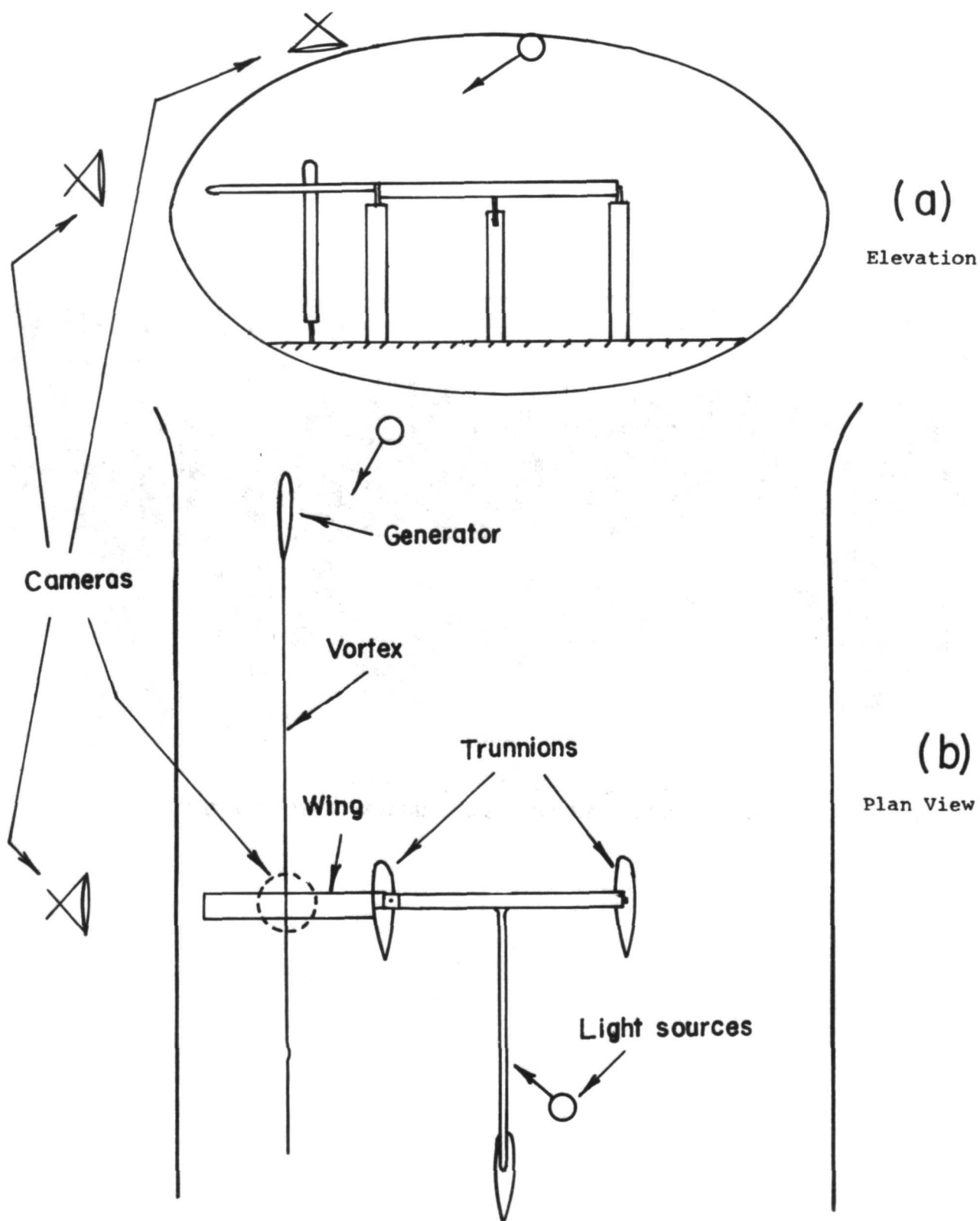


FIG. 3 LAYOUT OF THE EXPERIMENTS ON TRAILING-VORTEX-INTERSECTING AIRFOIL INTERACTION

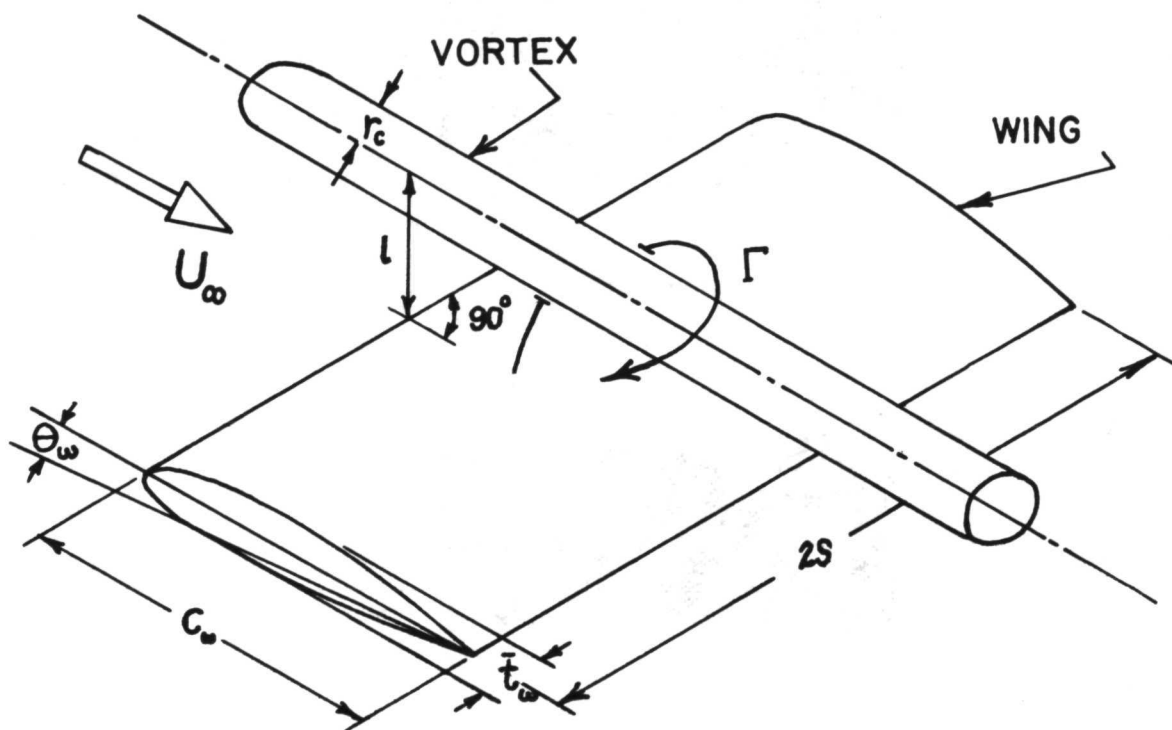
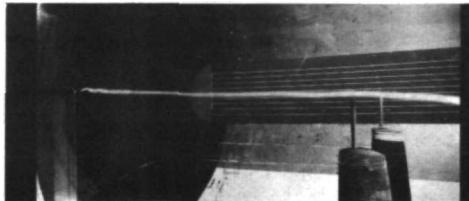
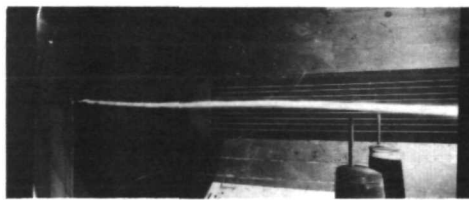
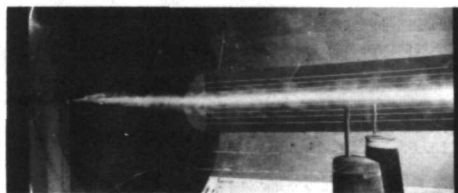
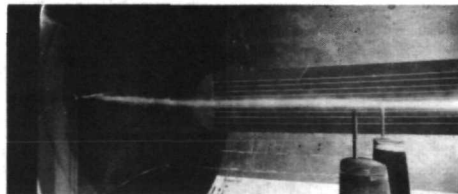


FIG. 4 SKETCH OF THE INTERACTION REGION

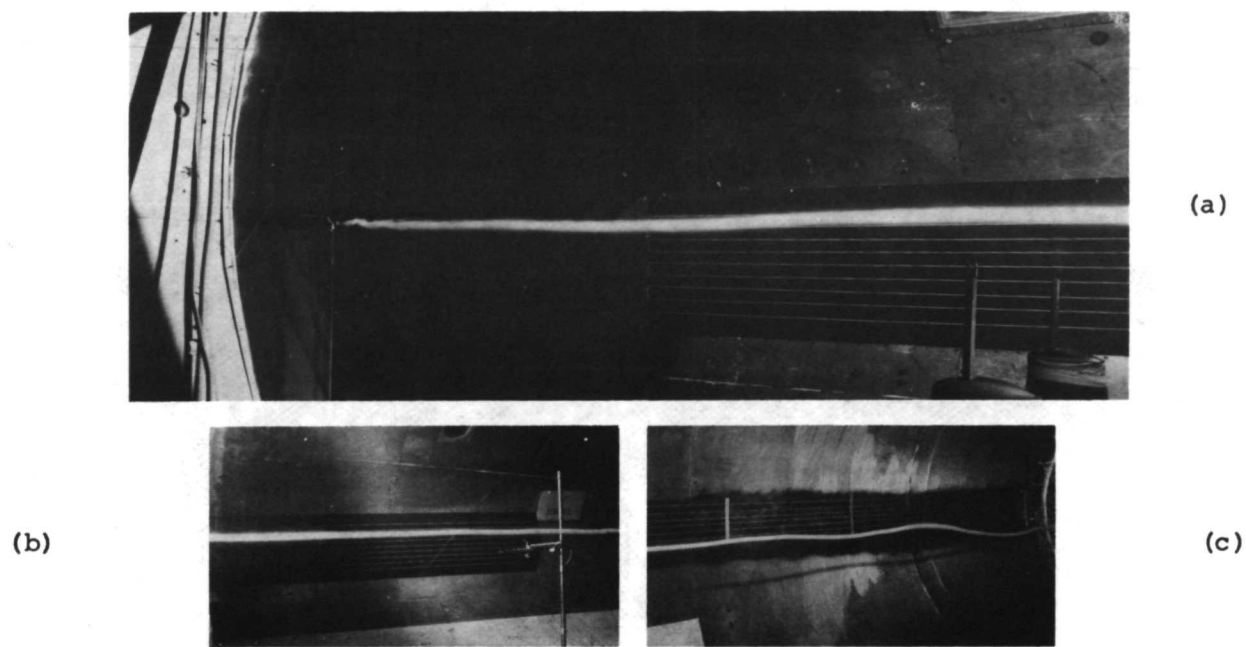


(a)  $\alpha = 0$

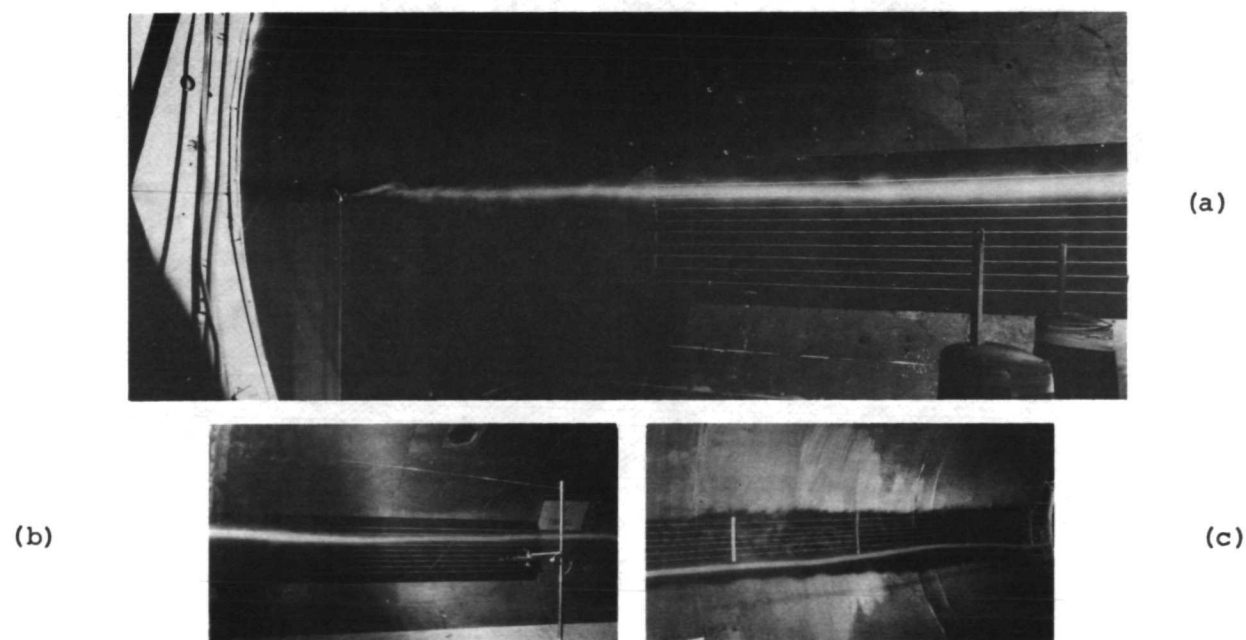


(b)  $\alpha = 0.1$

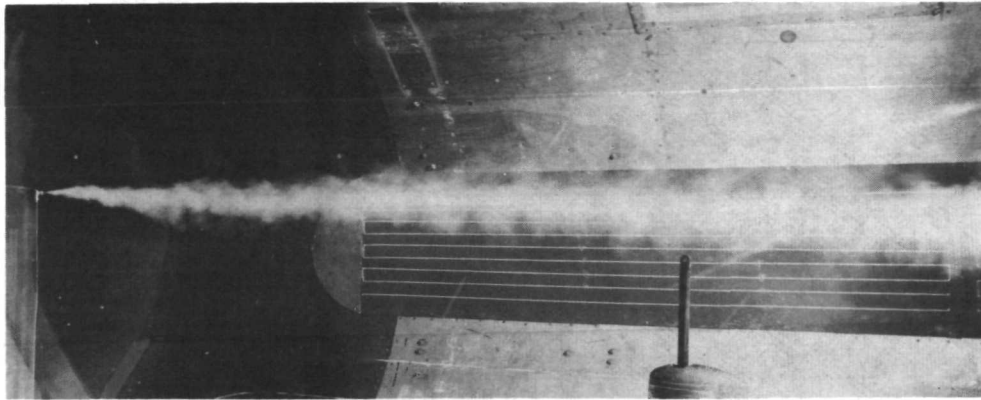
FIG. 5 PHOTOGRAPHS OF THE TRAILING VORTEX AT SAME INJECTION RATES  
(SAME VALUES OF  $\alpha$ ) BUT DIFFERENT AMOUNTS OF SMOKE INJECTION



(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section  
 FIG. 6 PHOTOGRAPHS OF THE TRAILING VORTEX WITHOUT INJECTION ( $\alpha = 0$ ,  $\beta = 0$ )

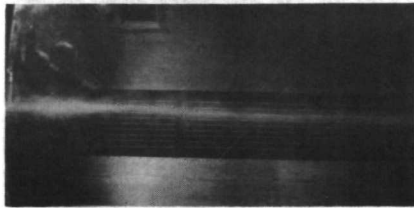


(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section  
 FIG. 7 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 0.1$ ,  $\beta = 0.73$ )

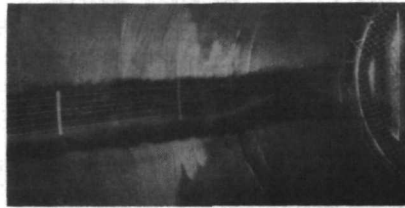


(a)

(b)

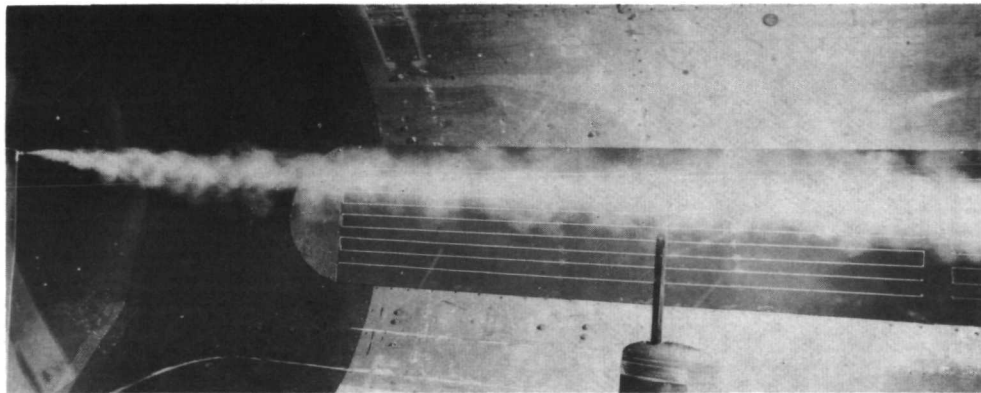


(c)



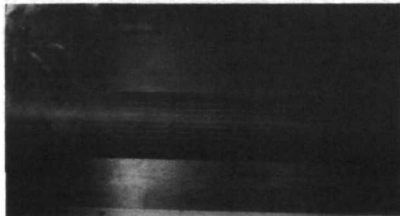
(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section

FIG. 8 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 0.2$ ,  $\beta = 1.14$ )

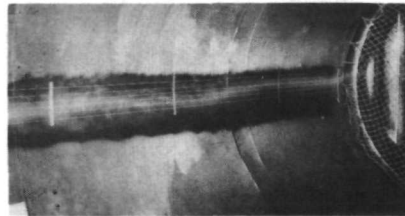


(a)

(b)

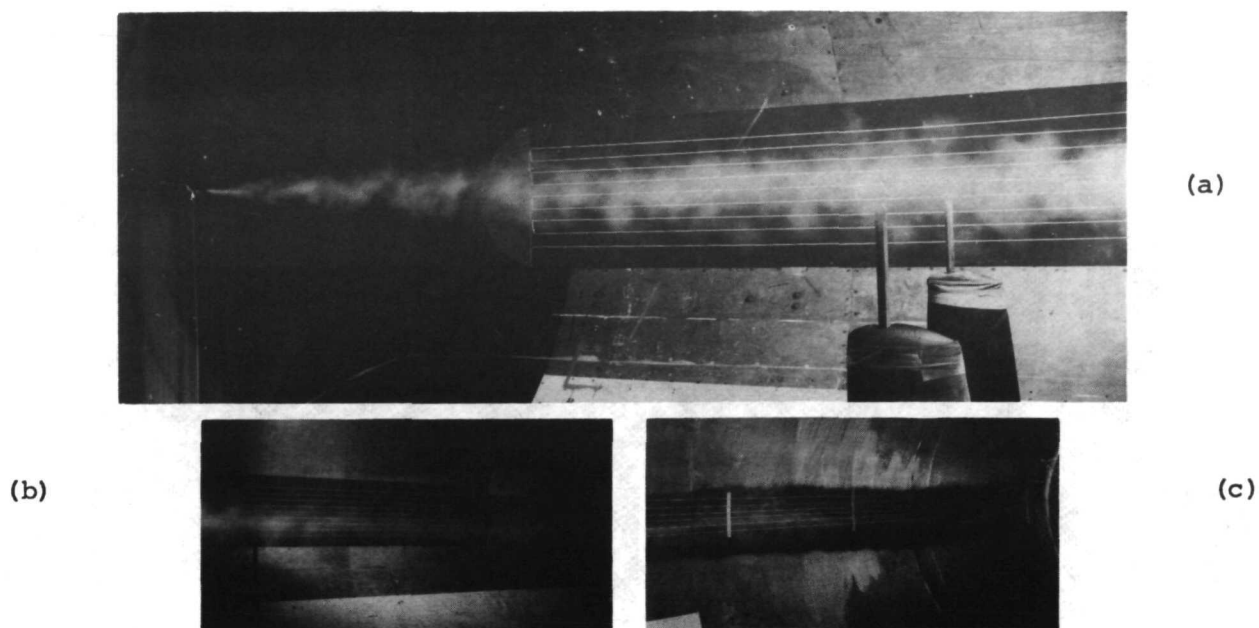


(c)



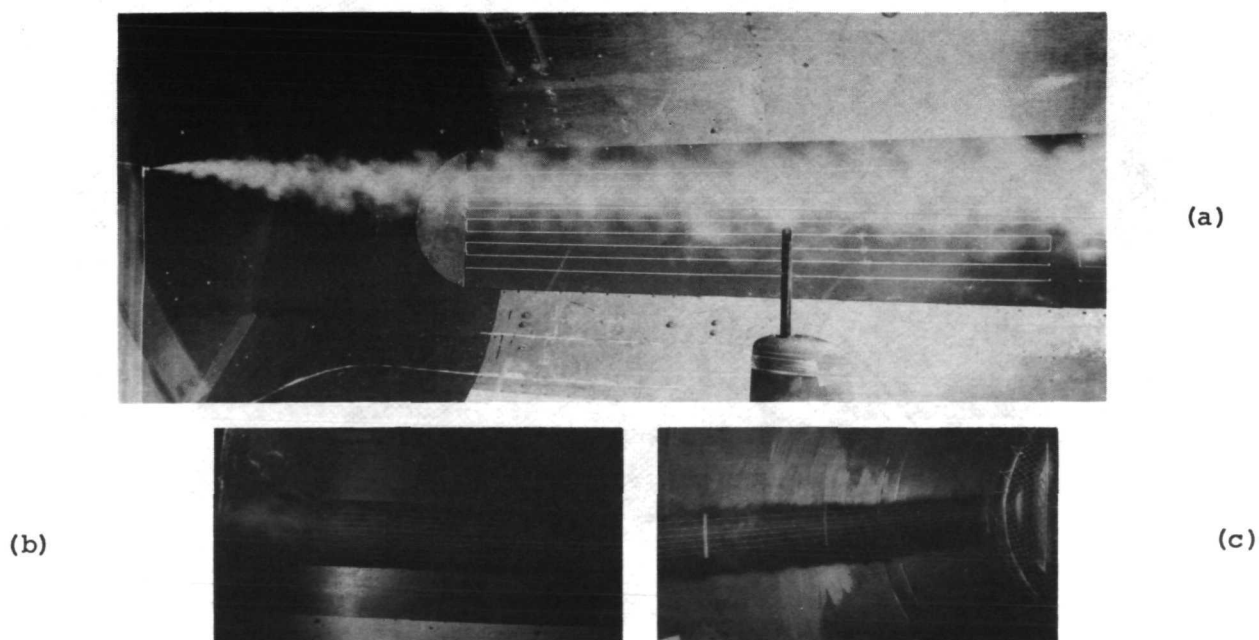
(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section

FIG. 9 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 0.3$ ,  $\beta = 1.36$ )



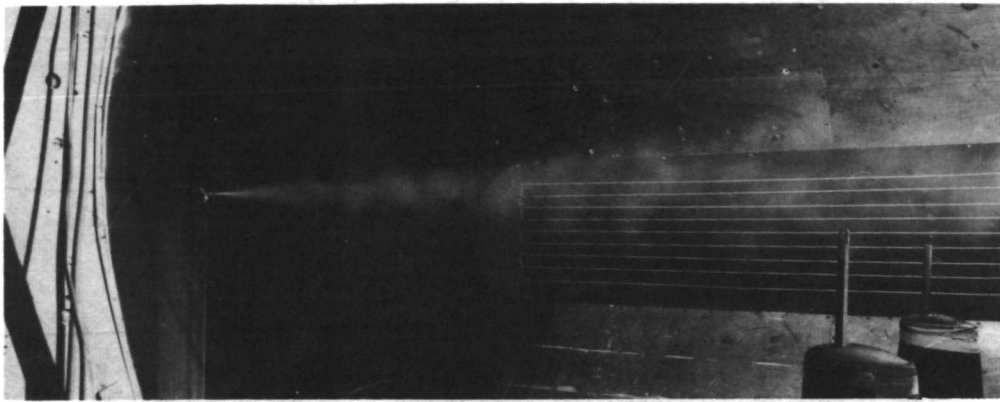
(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section

FIG. 10 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 0.4$ ,  $\beta = 3.30$ )

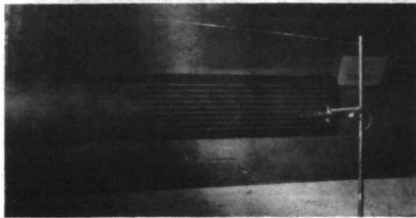


(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section

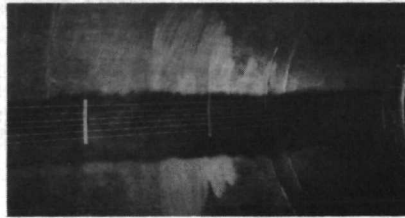
FIG. 11 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 0.6$ ,  $\beta = 1.90$ )



(a)



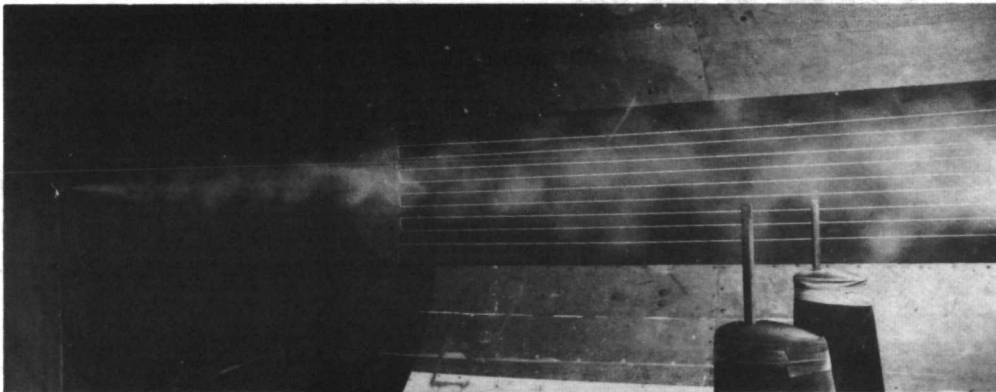
(b)



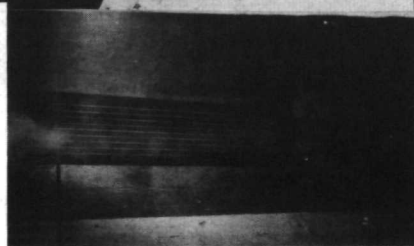
(c)

(a) Upstream Section; (b) Downstream Section; (c) Far Downstream Section

FIG. 12 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 0.9$ ,  $\beta = 4.00$ )



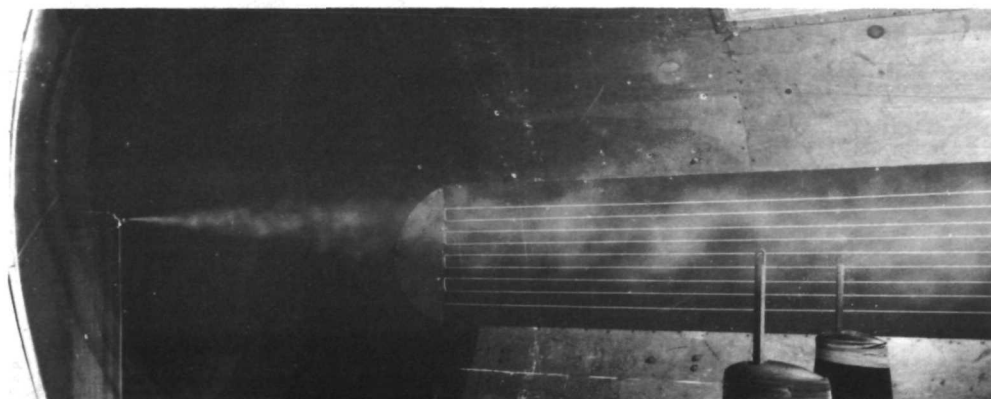
(a)



(b)

(a) Upstream Section; (b) Downstream Section

FIG. 13 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 1.04$ ,  $\beta = 5.70$ )



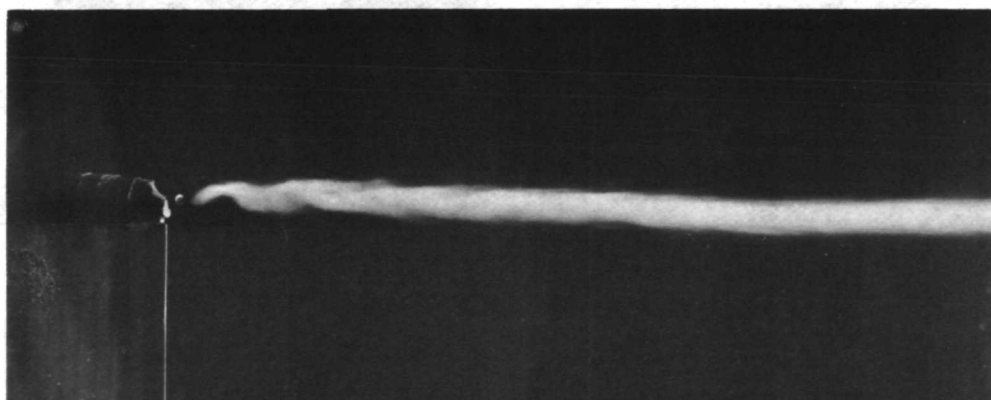
(a)



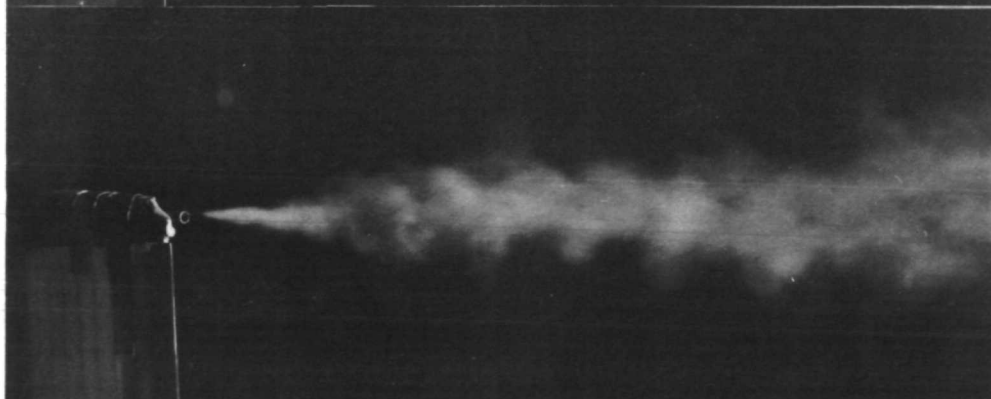
(b)

(a) Upstream Section; (b) Downstream Section

FIG. 14 PHOTOGRAPHS OF THE TRAILING VORTEX WITH INJECTION ( $\alpha = 2.10$ ,  $\beta = 4.10$ )



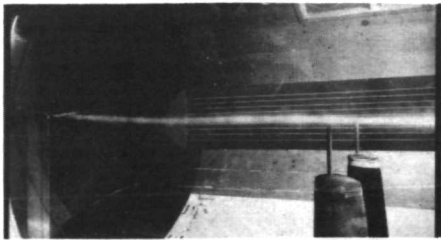
(a)



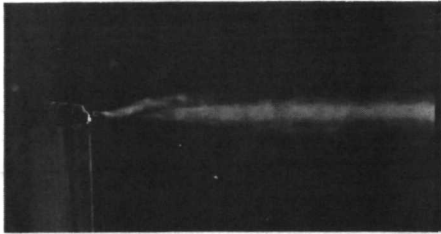
(b)

(a)  $\alpha = 0$ ; (b)  $\alpha = 0.4$

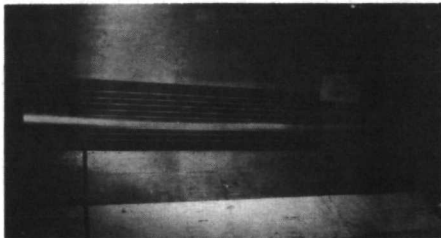
FIG. 15 CLOSE-UP PHOTOGRAPHS OF THE TRAILING VORTEX NEAR THE WING TRAILING EDGE WITH AND WITHOUT INJECTION



(a)

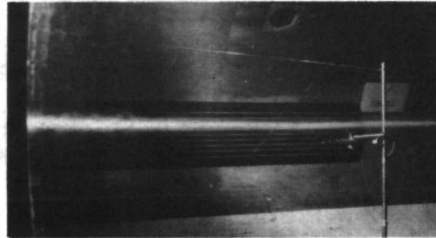
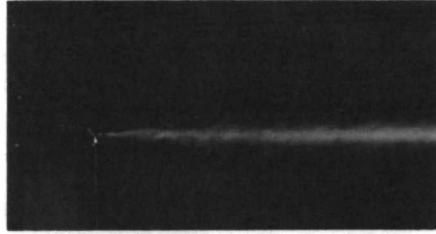
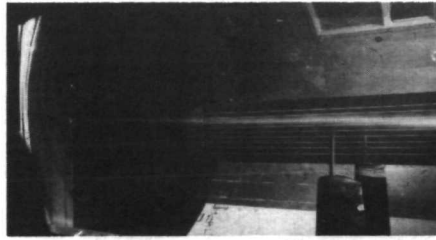


(b)

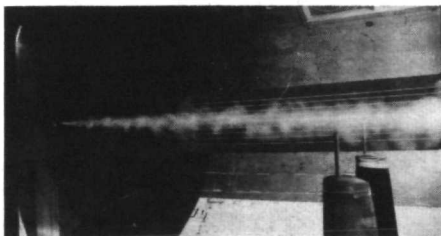


(c)

$\alpha = 0.1, \beta = 0.7$



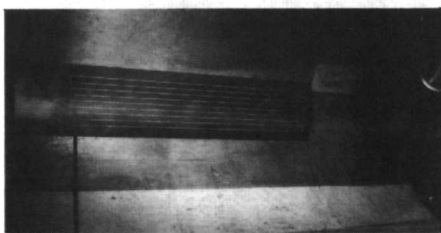
$\alpha = 0.1, \beta = 1.46$



(a)

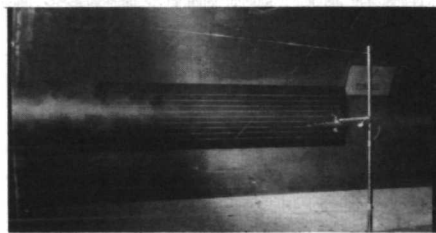
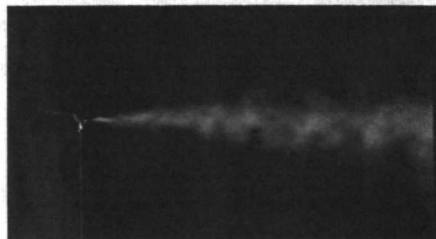
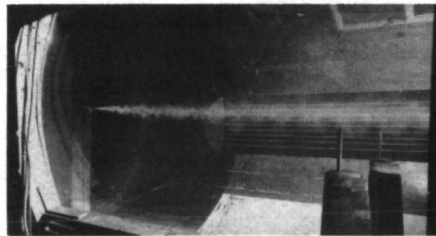


(b)



(c)

$\alpha = 0.35, \beta = 1.46$



$\alpha = 0.40, \beta = 3.30$

FIG. 16a PHOTOGRAPHS OF THE TRAILING VORTEX AT SIMILAR VALUES OF JET MOMENTUM FLOW RATE BUT DIFFERENT VALUES OF JET MASS FLOW RATE. (a) UPSTREAM SECTION; (b) CLOSE-UP VIEW OF THE SECTION NEAR THE WING TRAILING EDGE; (c) DOWNSTREAM SECTION

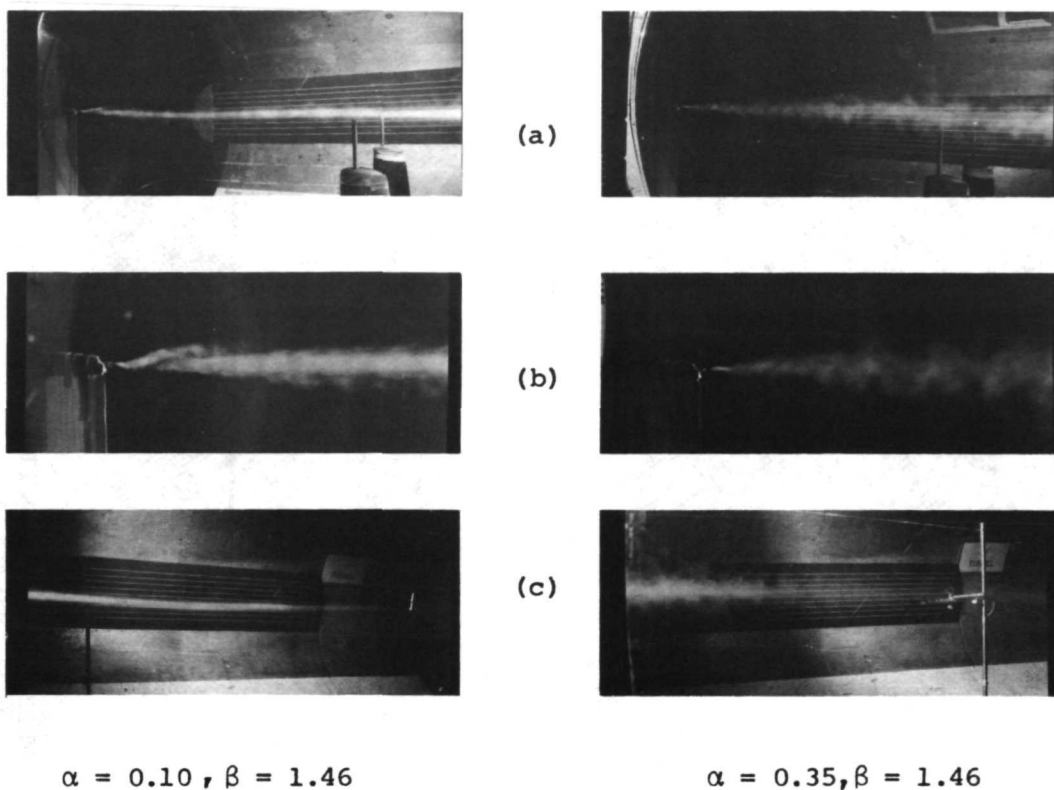


FIG. 16b PHOTOGRAPHS OF THE TRAILING VORTEX AT THE SAME VALUE OF JET MASS FLOW RATE BUT DIFFERENT VALUES OF JET MOMENTUM FLOW RATE. (a) UPSTREAM SECTION; (b) CLOSE-UP VIEW OF THE SECTION NEAR THE WING TRAILING EDGE; (c) DOWNSTREAM SECTION

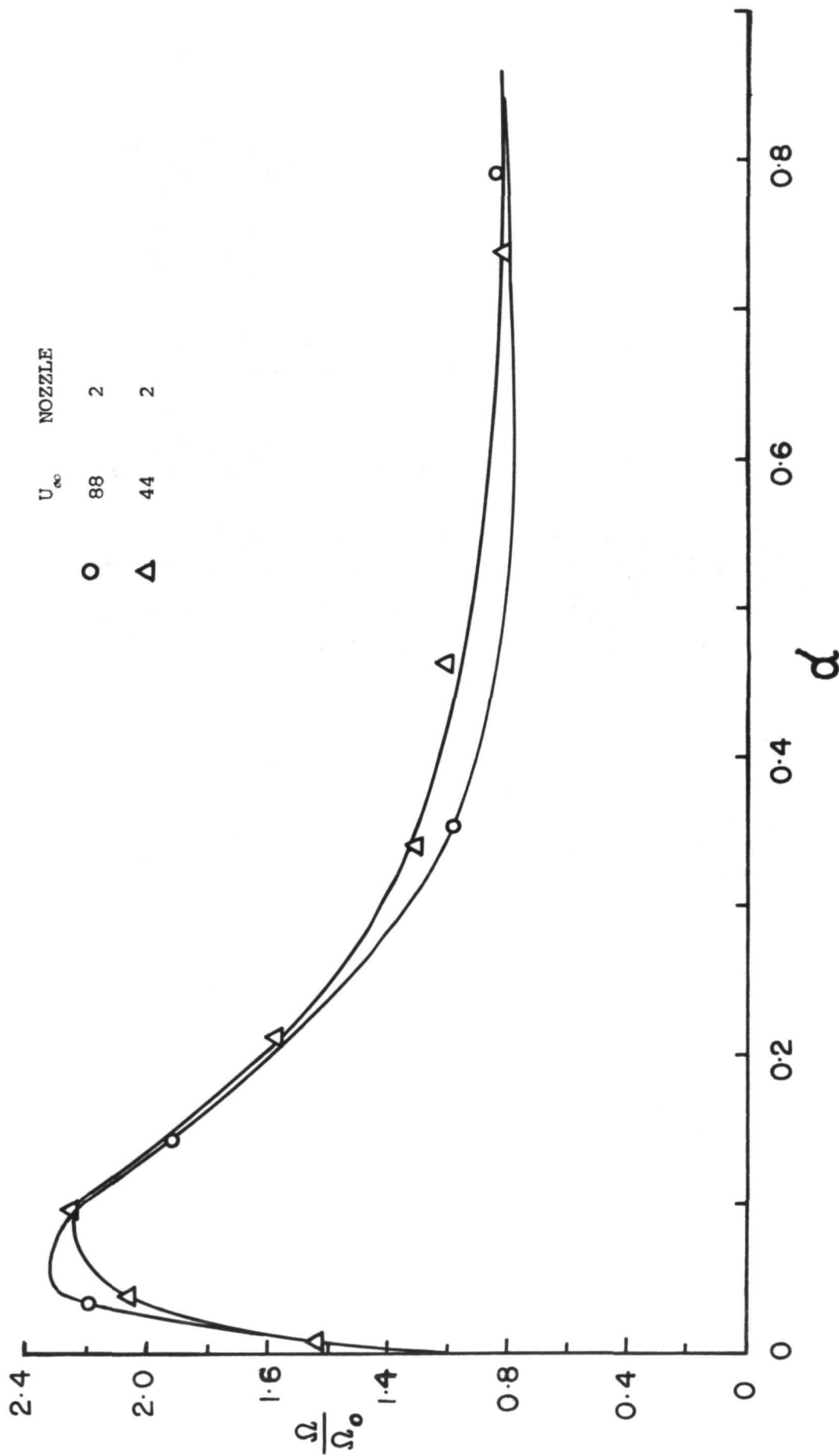


FIG. 17a VARIATION OF  $\Omega/\Omega_0$  WITH  $\alpha$  FOR DIFFERENT FREE-STREAM VELOCITIES (44 & 88 FPS - NOZZLE No.2), MEASUREMENTS MADE AT 1c DOWNSTREAM OF THE WING TRAILING EDGE

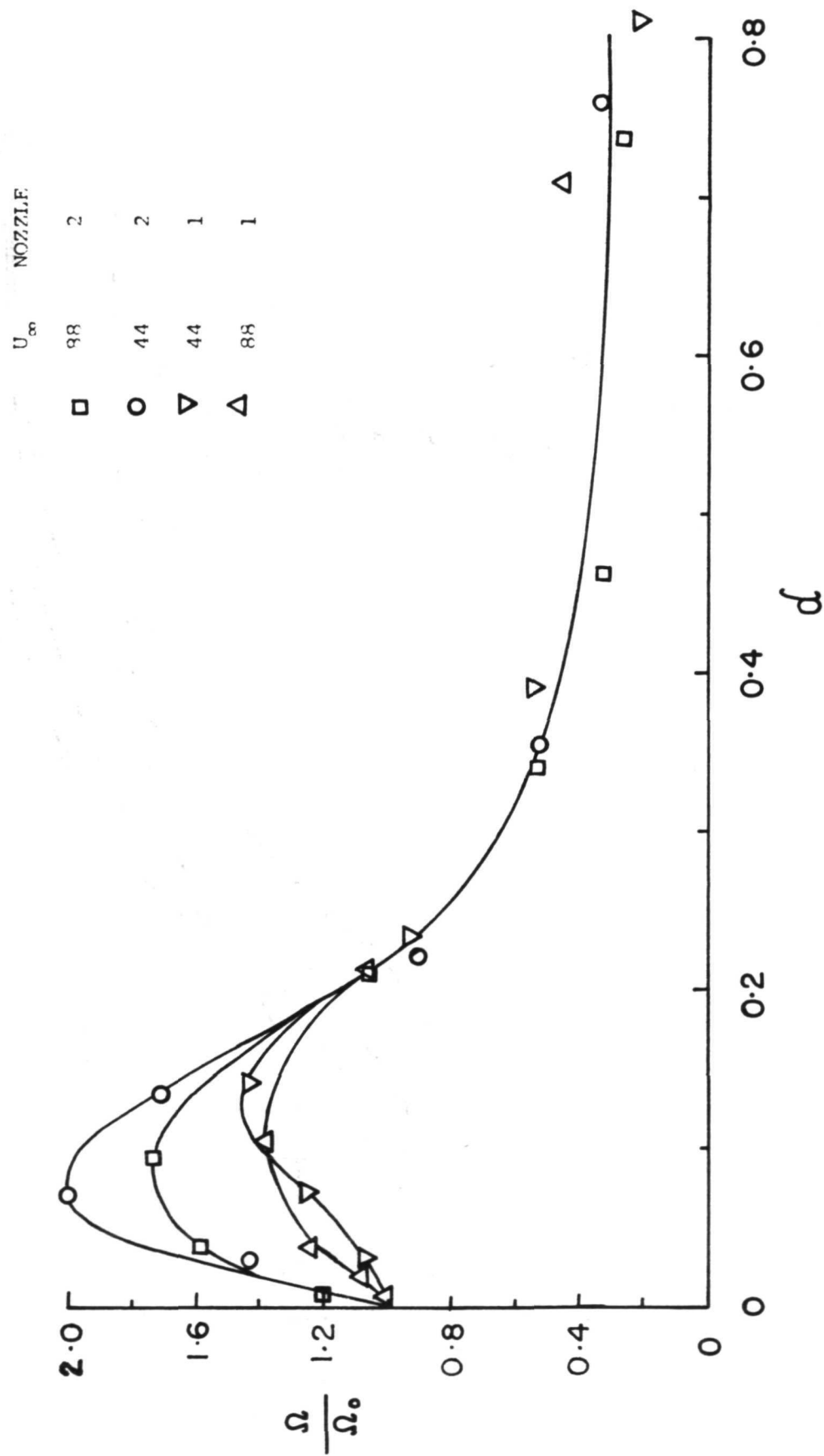


FIG. 17b VARIATION OF  $\Omega/\Omega_0$  WITH  $d$  FOR DIFFERENT FREE-STREAM VELOCITIES (44 & 88 FPS - NOZZLE NOS. 1 & 2), MEASUREMENTS MADE AT 3c DOWNSTREAM OF THE WING TRAILING EDGE

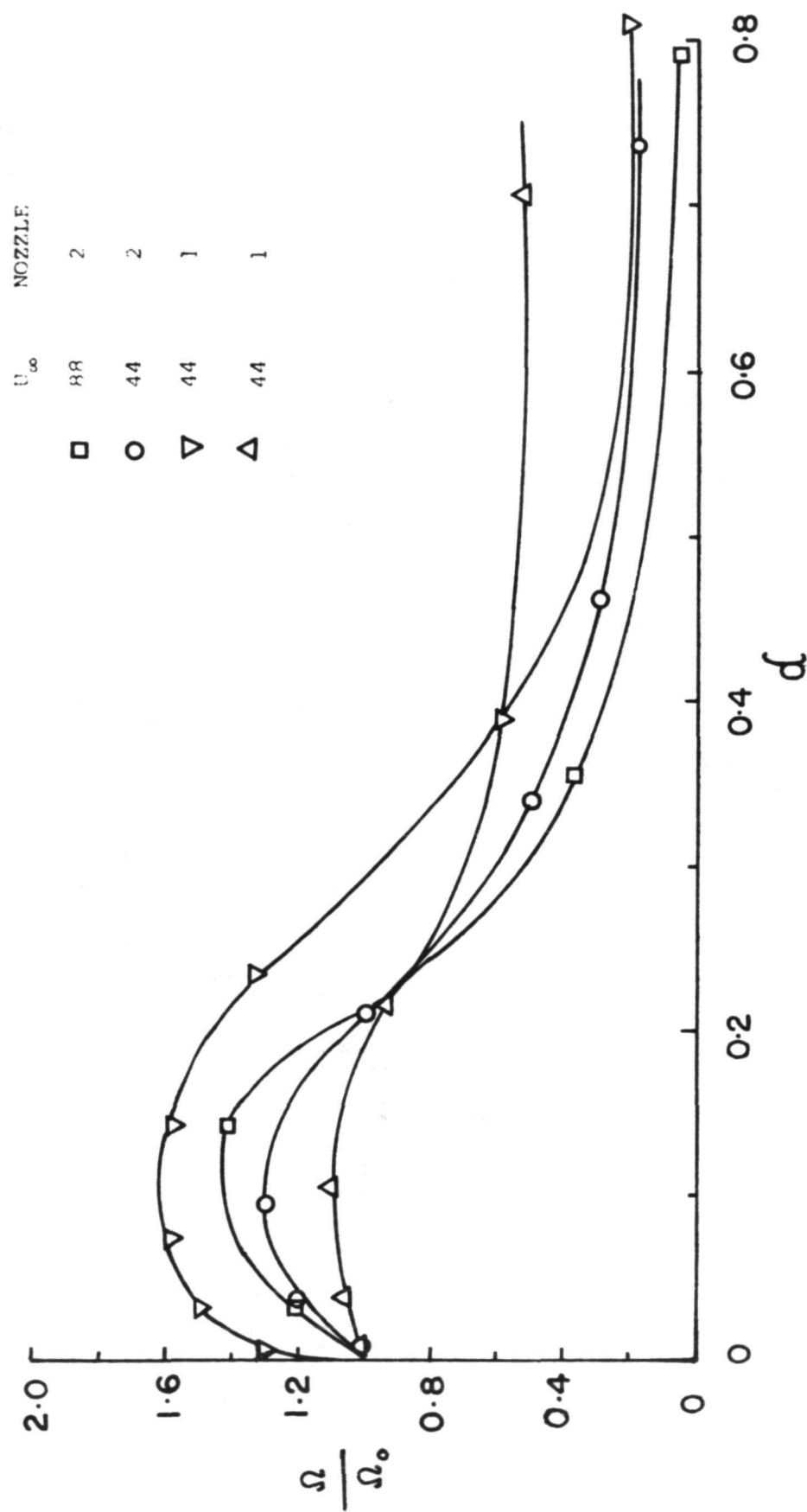


FIG. 17c VARIATION OF  $\Omega/\Omega_0$  WITH  $\alpha$  FOR DIFFERENT FREE-STREAM VELOCITIES (44 & 88 FPS - NOZZLE NOS. 1 & 2), MEASUREMENTS MADE AT 13c DOWNSTREAM OF THE WING TRAILING EDGE

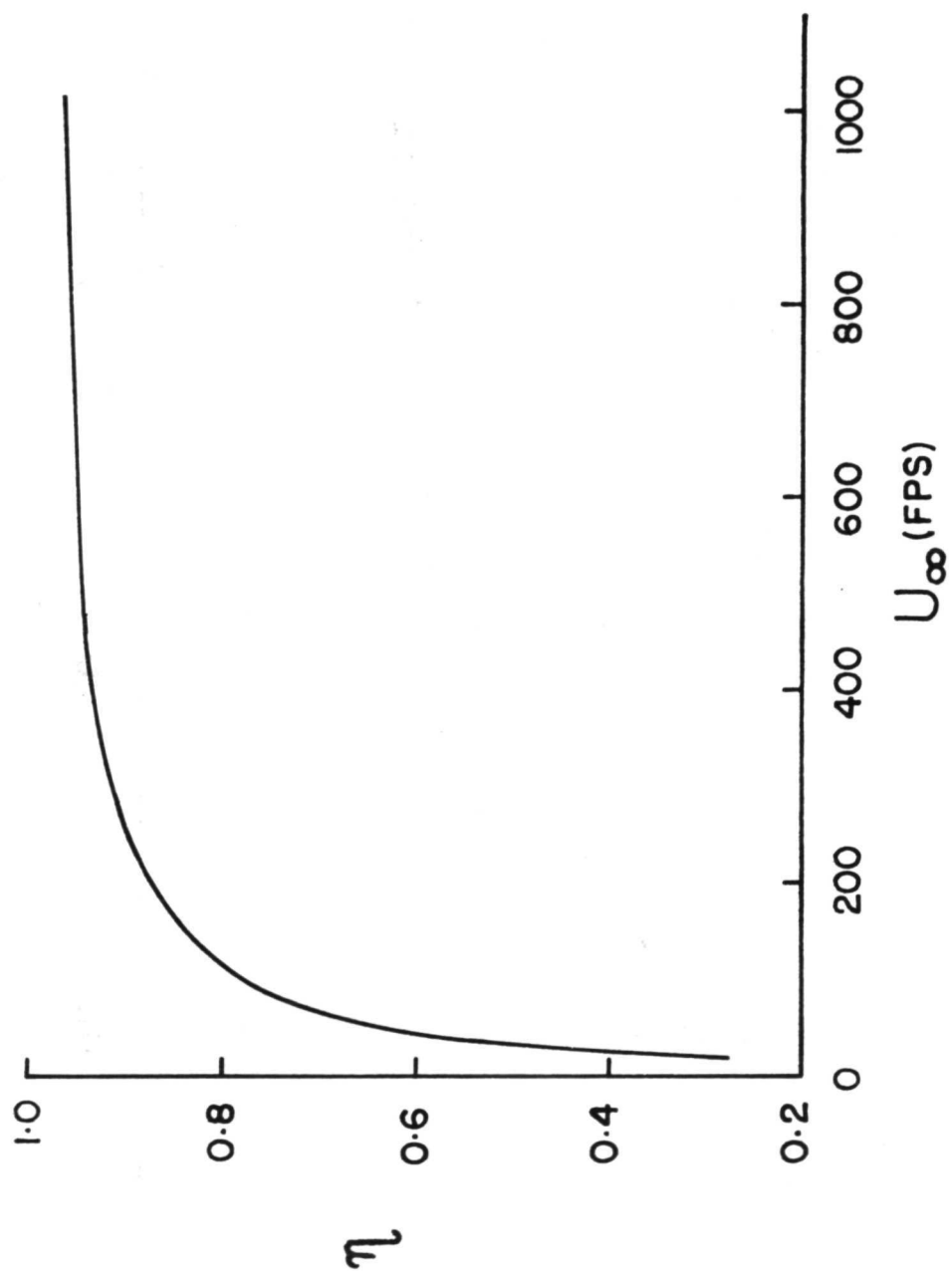


FIG. 18 EFFICIENCY OF THE VORTICITY METER AT DIFFERENT FREE-STREAM VELOCITIES

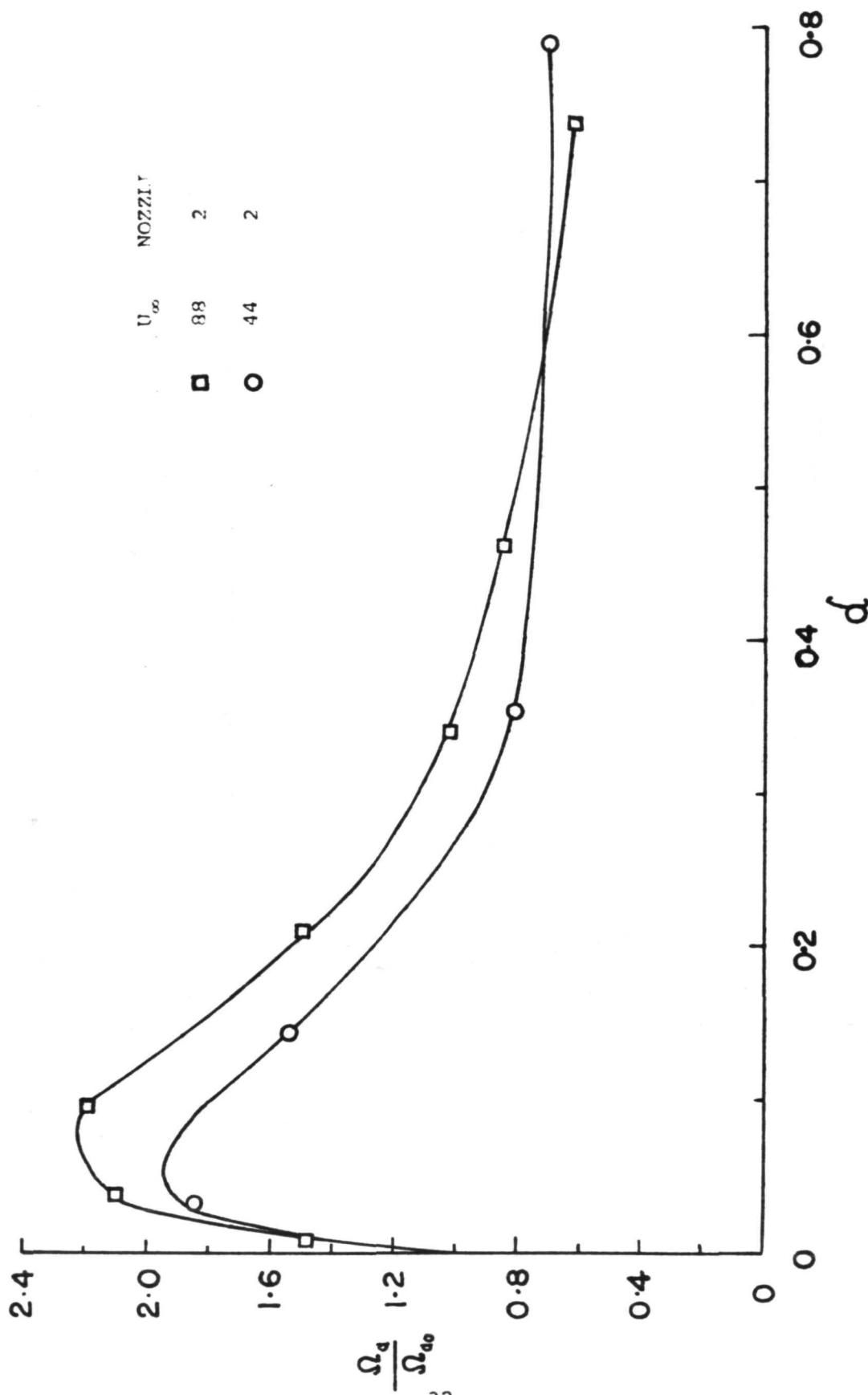


FIG. 19a VARIATION OF  $\Omega_a / \Omega_{a_0}$  WITH  $\alpha$  FOR DIFFERENT FREE-STREAM VELOCITIES (44 & 88 FPS - NOZZLE No.2), MEASUREMENTS MADE AT 1c DOWNSTREAM OF THE WING TRAILING EDGE

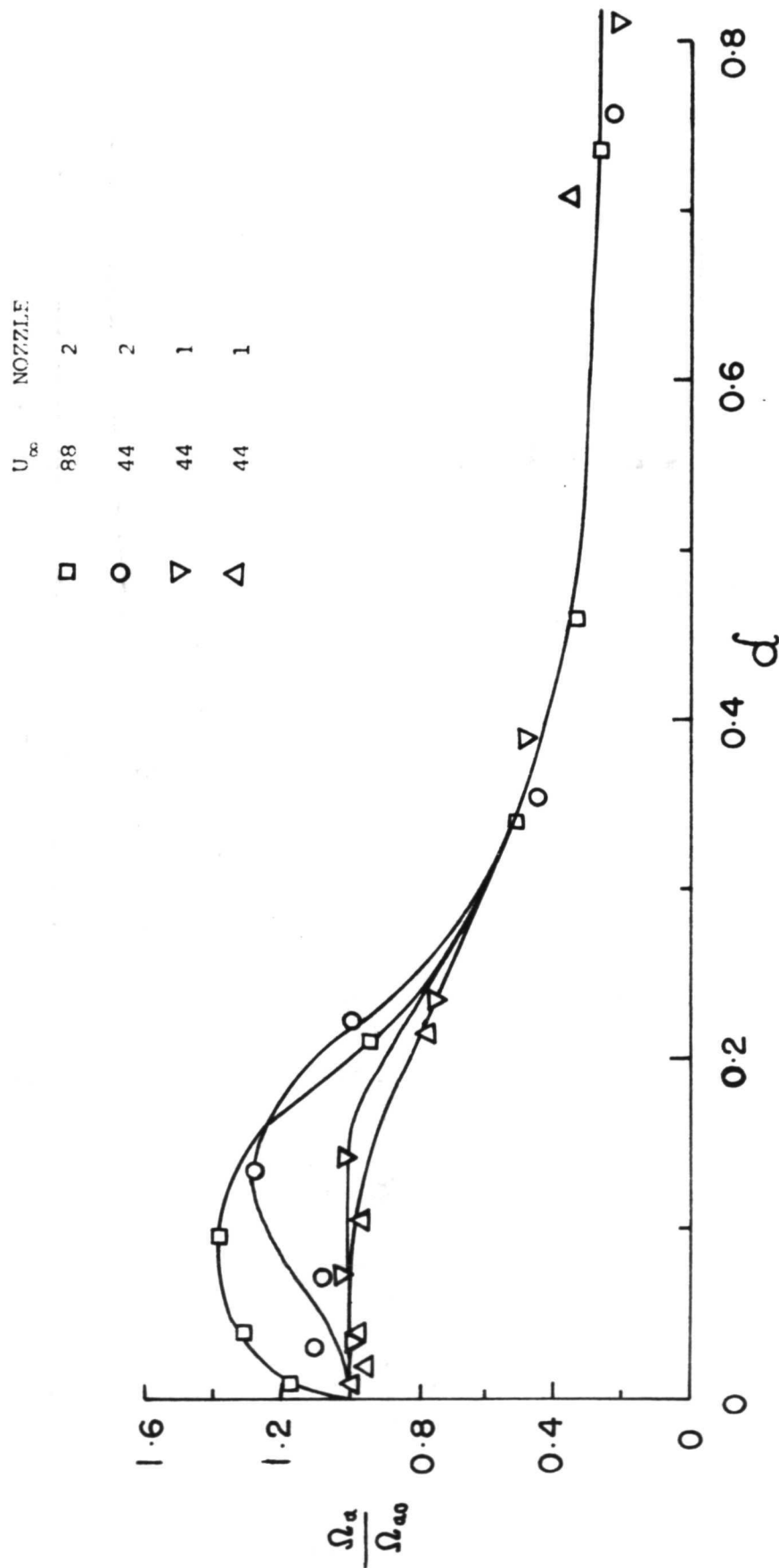


FIG. 19b VARIATION OF  $\Omega_a/\Omega_{a0}$  WITH  $\alpha$  FOR DIFFERENT FREE-STREAM VELOCITIES (44 & 88 FPS - NOZZLE NOS. 1 & 2), MEASUREMENTS MADE AT 3c DOWNSTREAM OF THE WING TRAILING EDGE

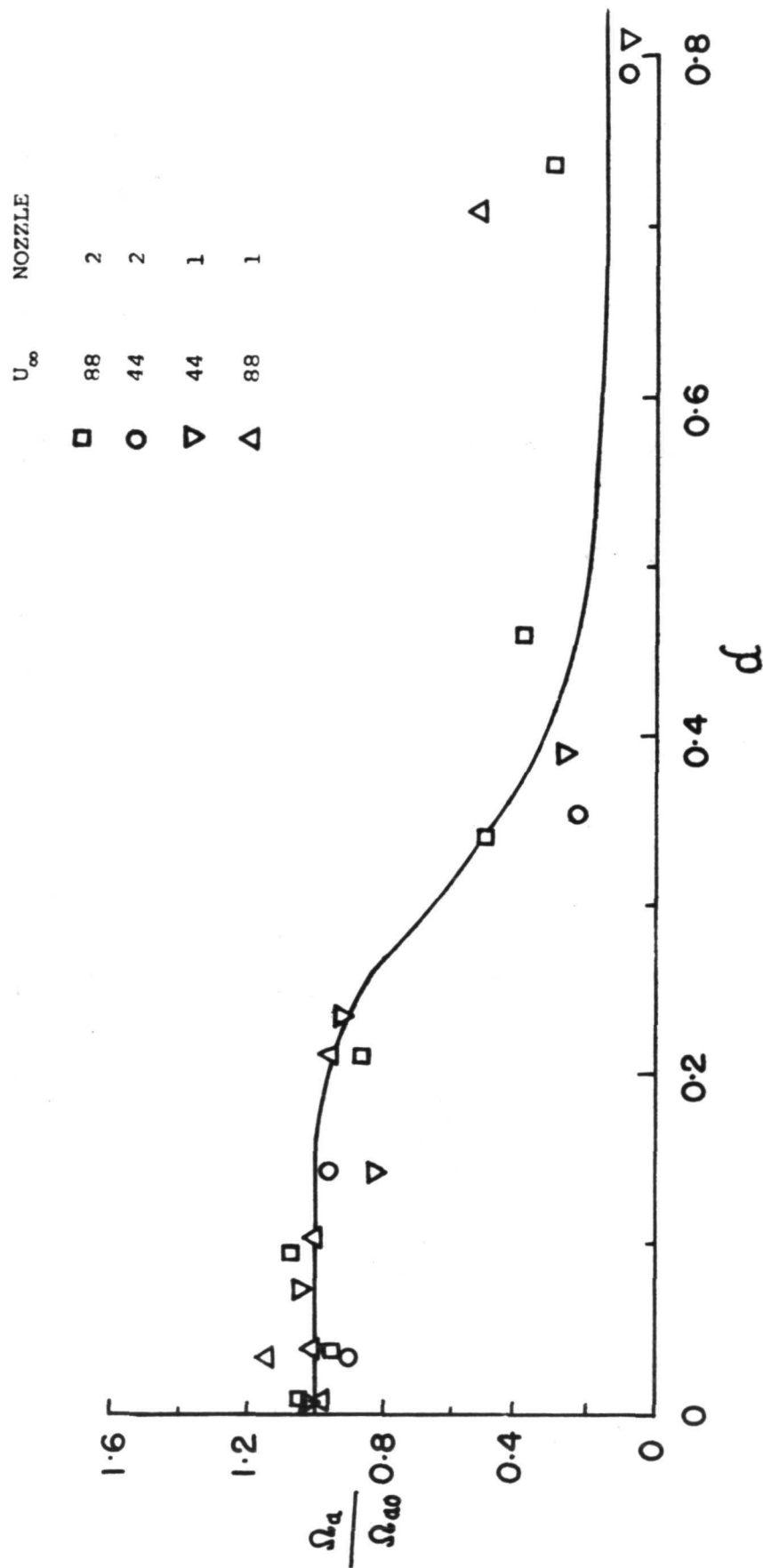
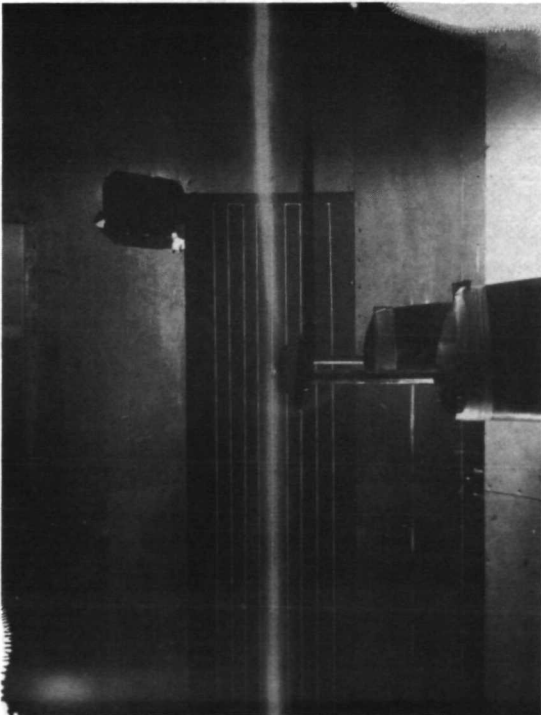
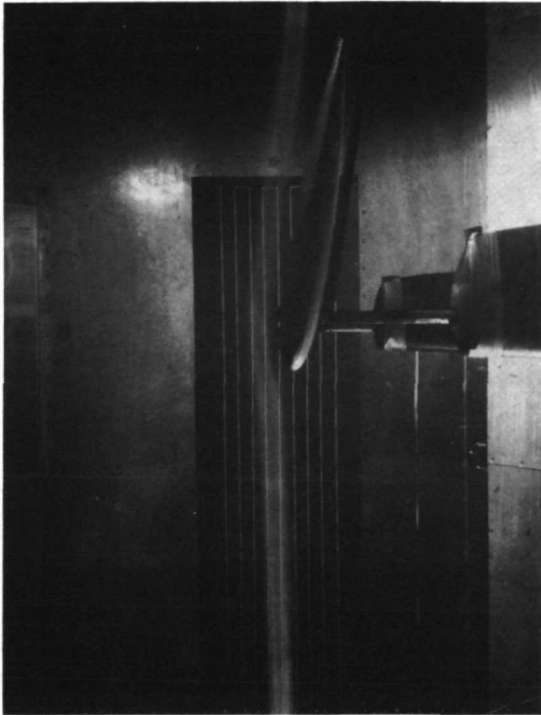


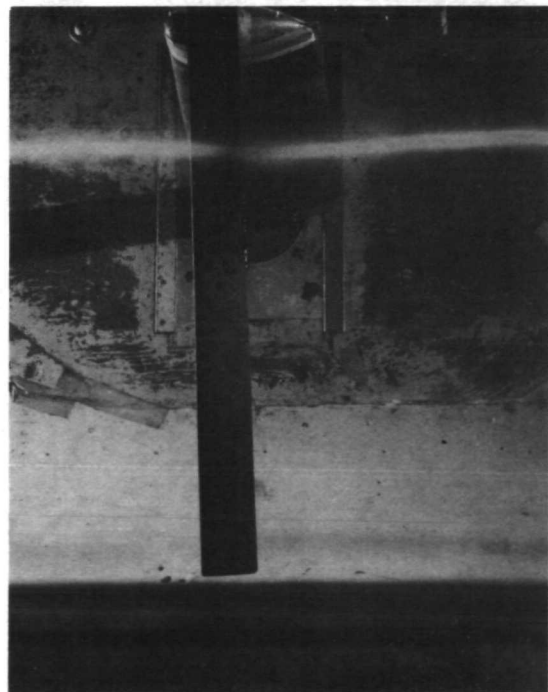
FIG. 19c VARIATION OF  $\Omega_a / \Omega_{a0}$  WITH  $d$  FOR DIFFERENT FREE-STREAM VELOCITIES (44 & 88 FPS - NOZZLE NOS. 1 & 2), MEASUREMENTS MADE AT 13c DOWNSTREAM OF THE WING TRAILING EDGE



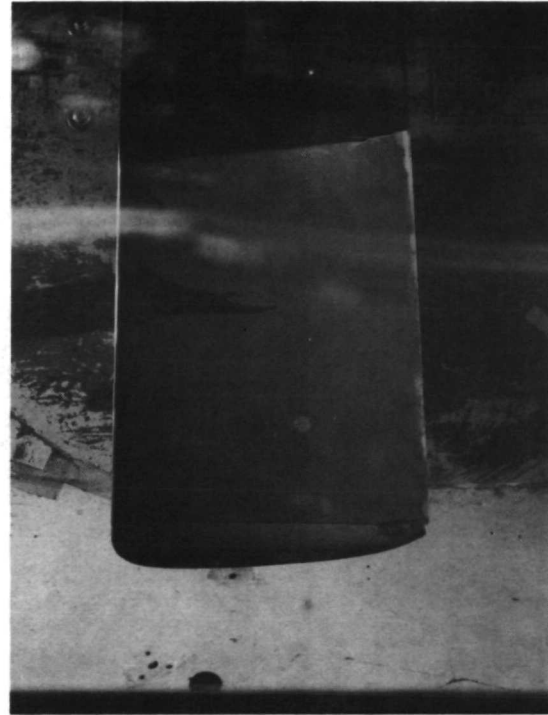
Side View



Side View

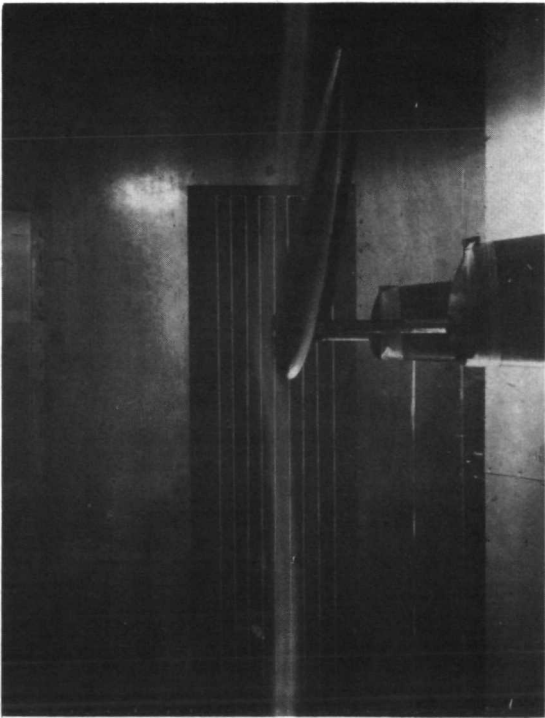


Plan View  
FIG. 20  $\theta_g = 8^\circ$ ,  $\lambda = 5.50$



Plan View  
FIG. 21  $\theta_g = 2^\circ$ ,  $\lambda = 0.6$

PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



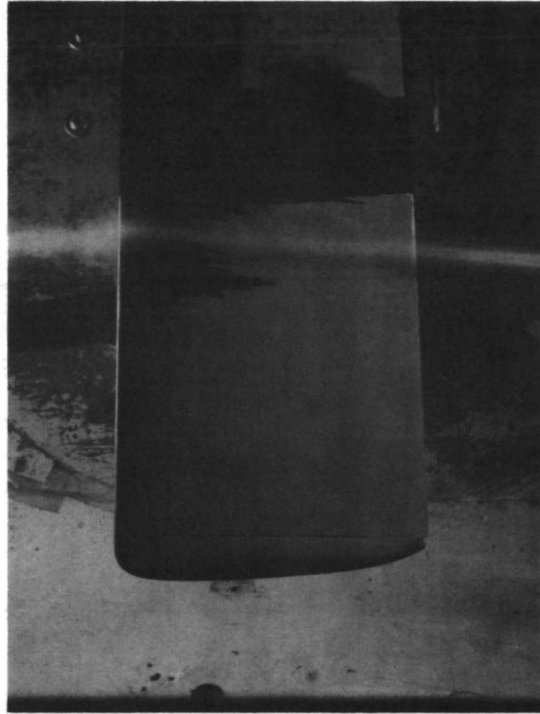
Side View



Side View



Plan View

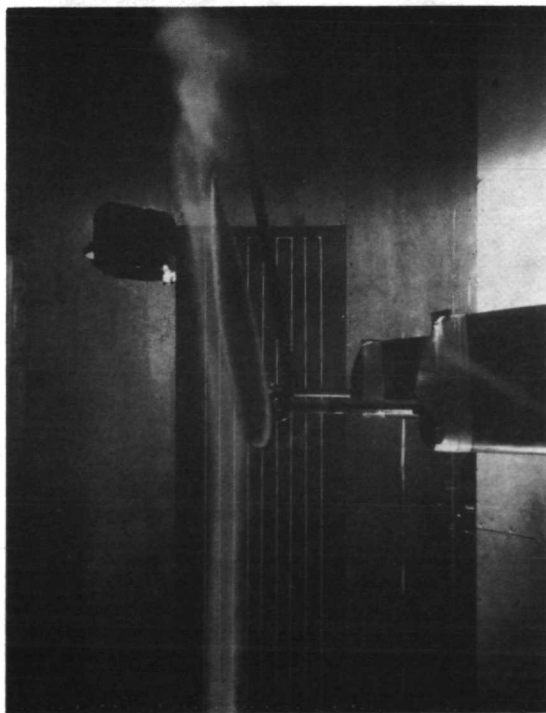


Plan View

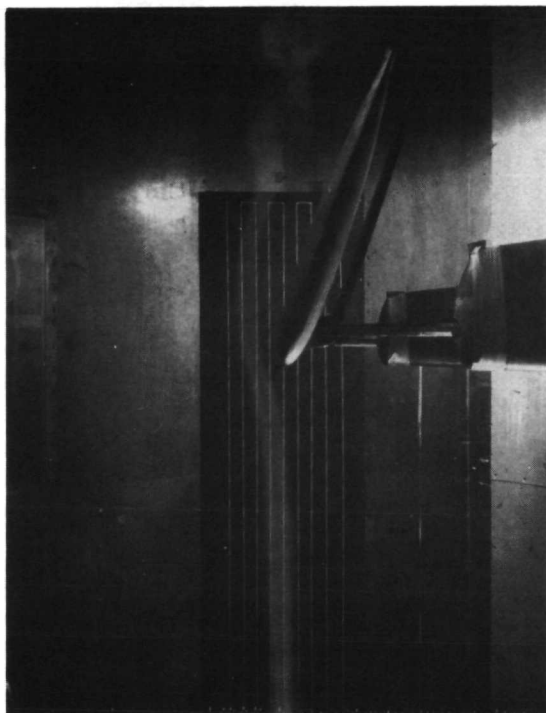
FIG. 22  $\theta_g = 8^\circ$ ,  $\lambda = 5.50$

FIG. 23  $\theta_g = 2^\circ$ ,  $\lambda = 10.90$

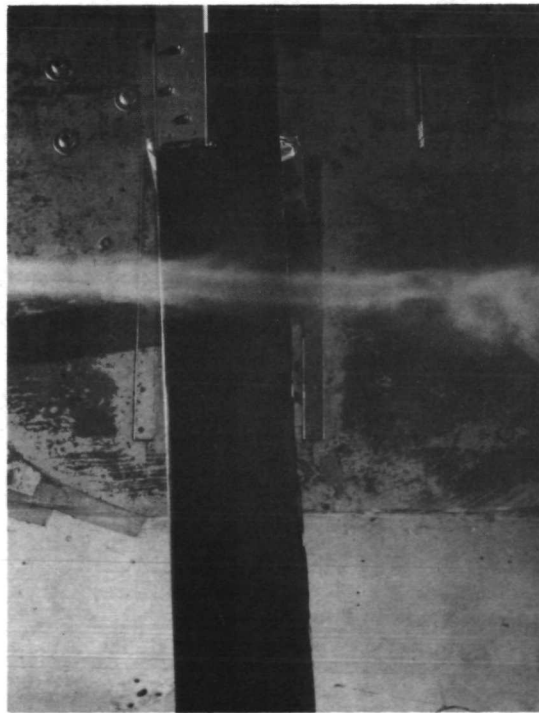
PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



Side View

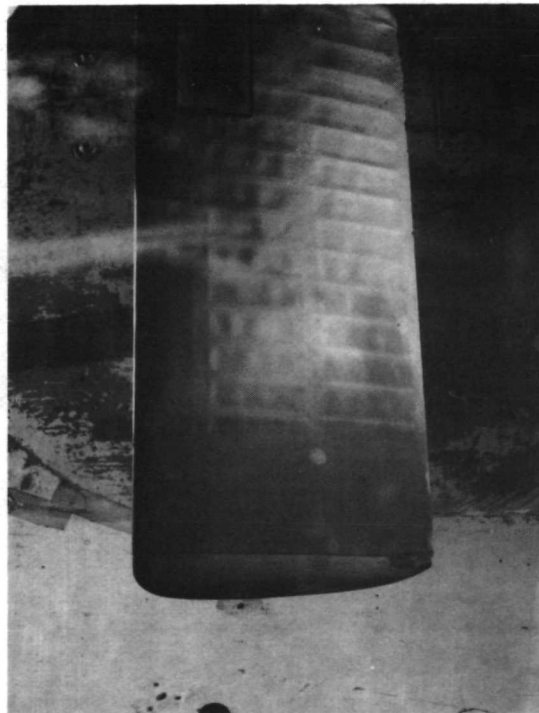


Side View



Plan View

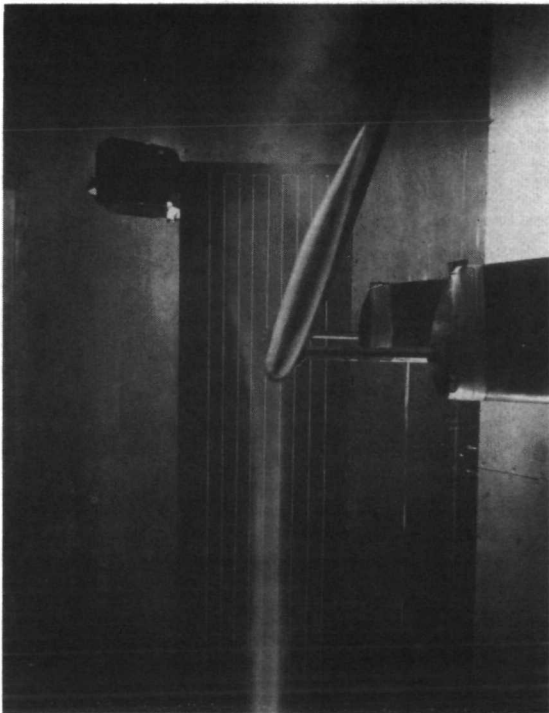
FIG. 24  $\theta_g = 8^\circ, \lambda = 2.40$



Plan View

FIG. 25  $\theta_g = 2^\circ, \lambda = 18.40$

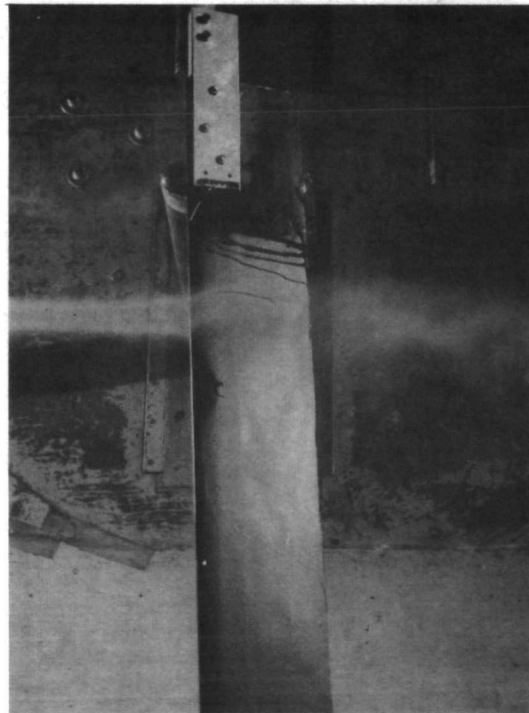
PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



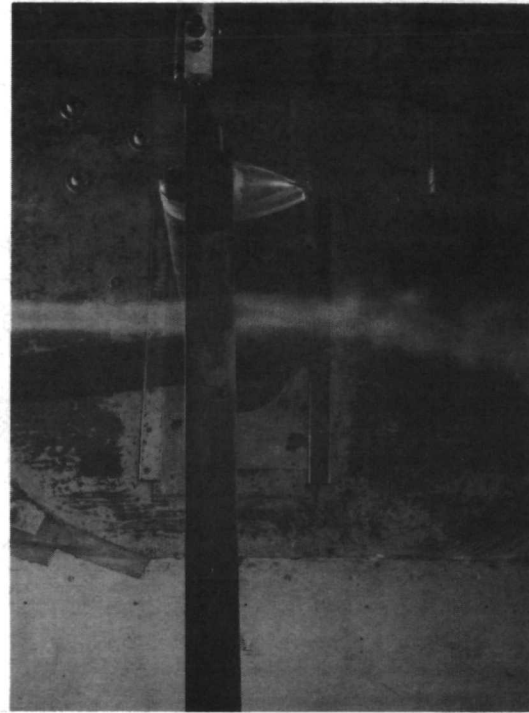
Side View



Side View



Plan View

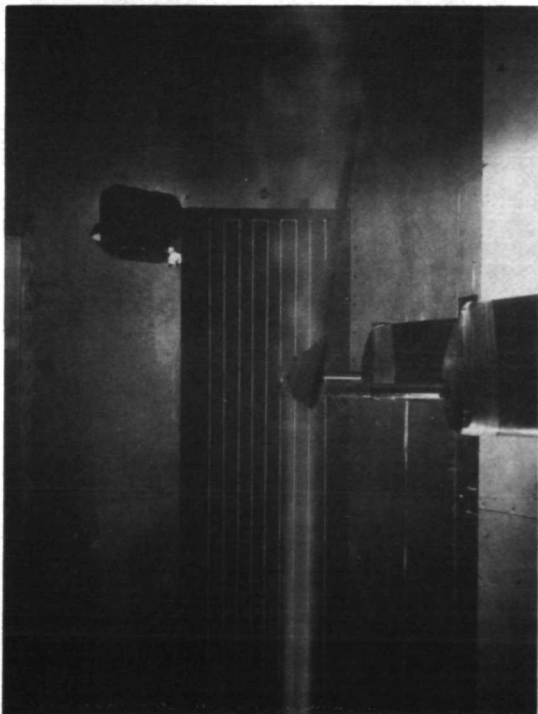


Plan View

FIG. 26  $\theta_g = 8^\circ$ ,  $\lambda = 4.00$

FIG. 27  $\theta_g = 8^\circ$ ,  $\lambda = 1.00$

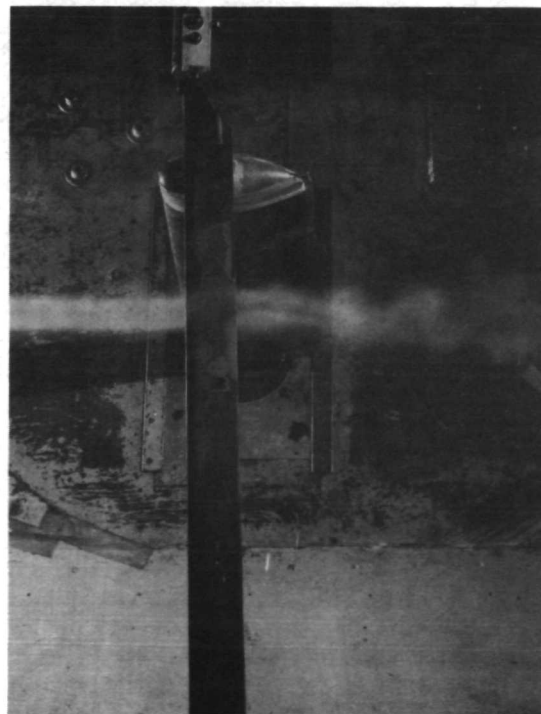
PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



Side View



Side View



Plan View

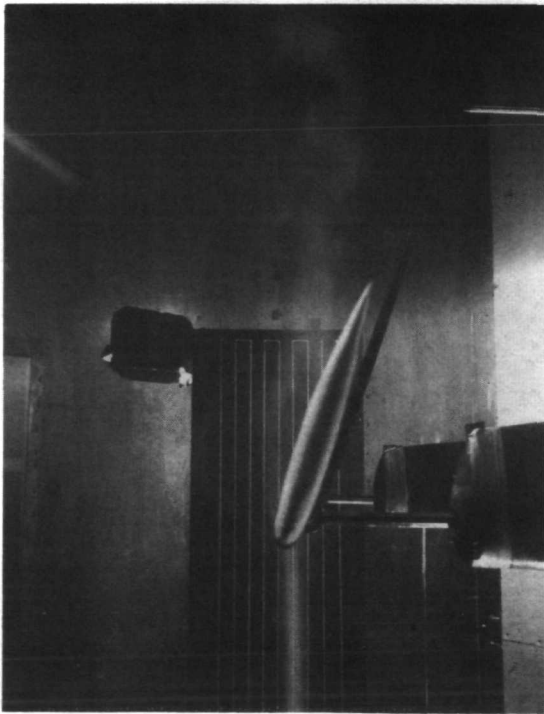
FIG. 28  $\theta_g = 8^\circ$ ,  $\lambda = 1.00$



Plan View

FIG. 29  $\theta_g = 2^\circ$ ,  $\lambda = 18.40$

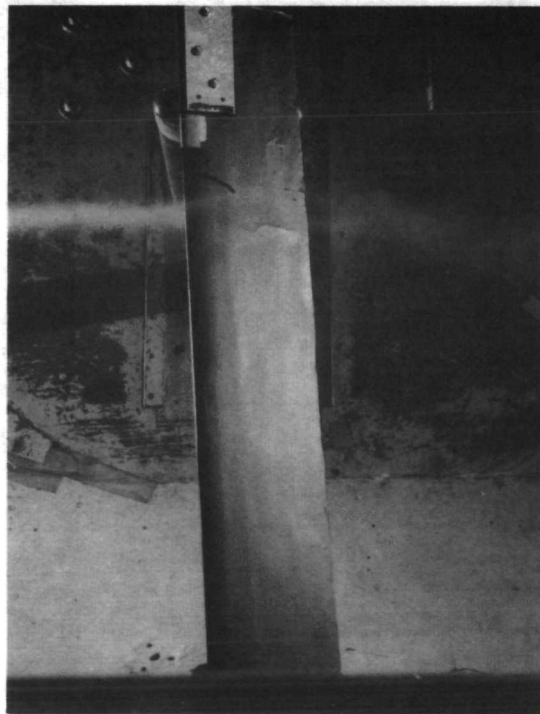
PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



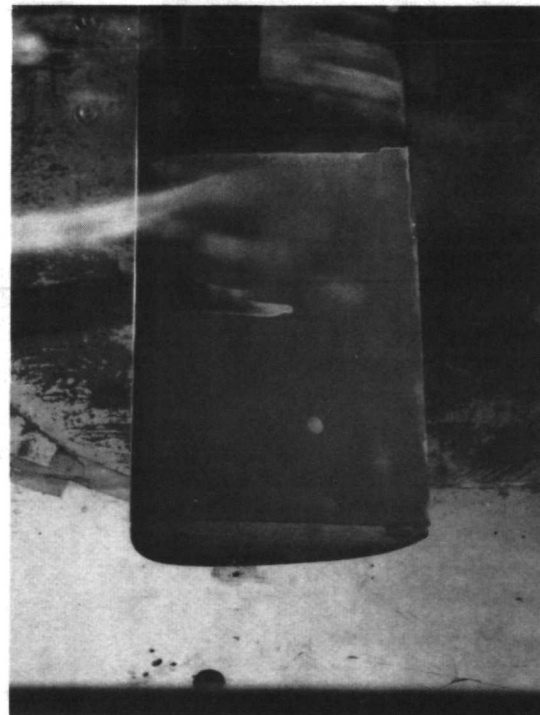
Side View



Side View



Plan View

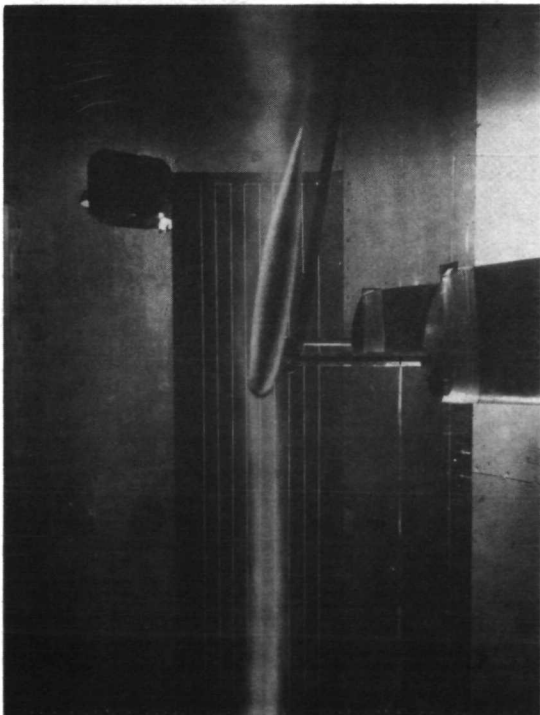


Plan View

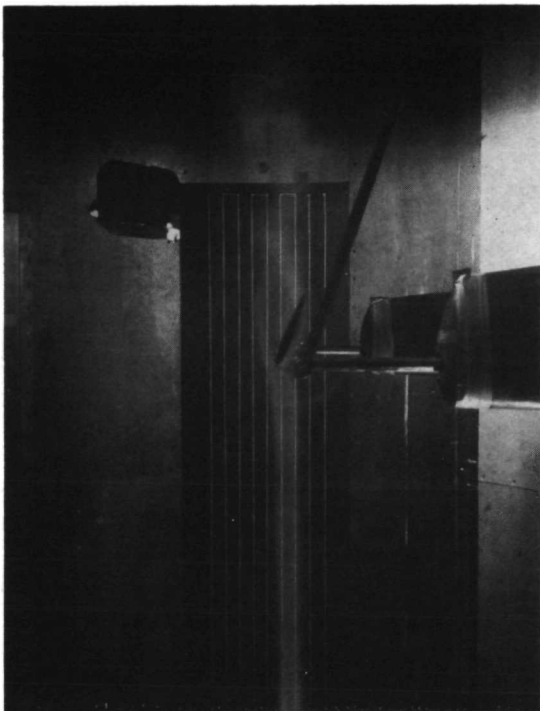
FIG. 30  $\theta_g = 2^\circ$ ,  $\lambda = 8.00$

FIG. 31  $\theta_g = 8^\circ$ ,  $\lambda = 9.20$

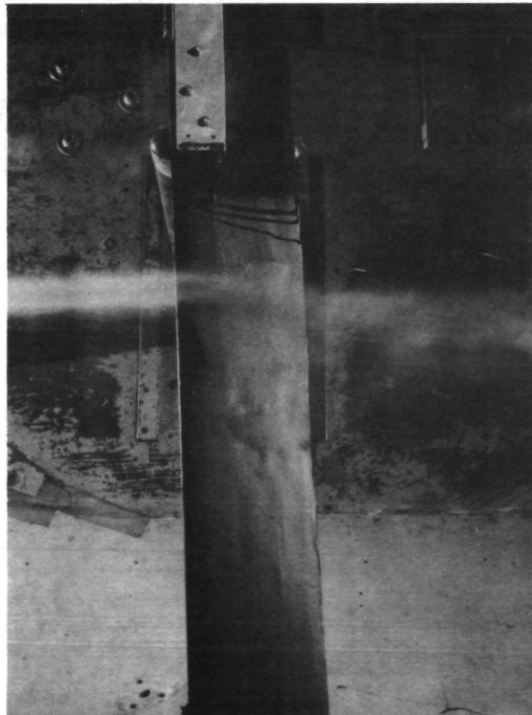
PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



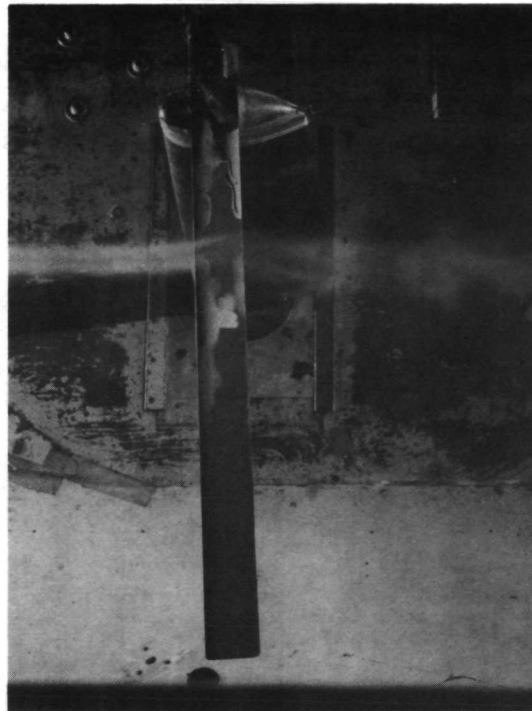
Side View



Side View



Plan View

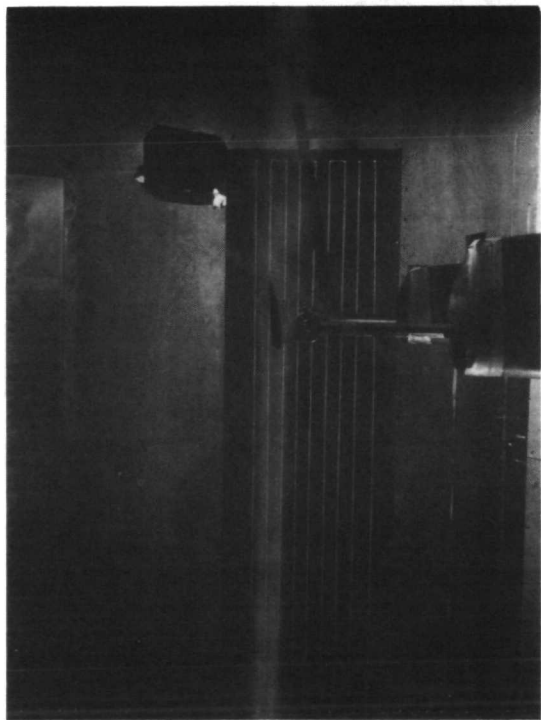


Plan View

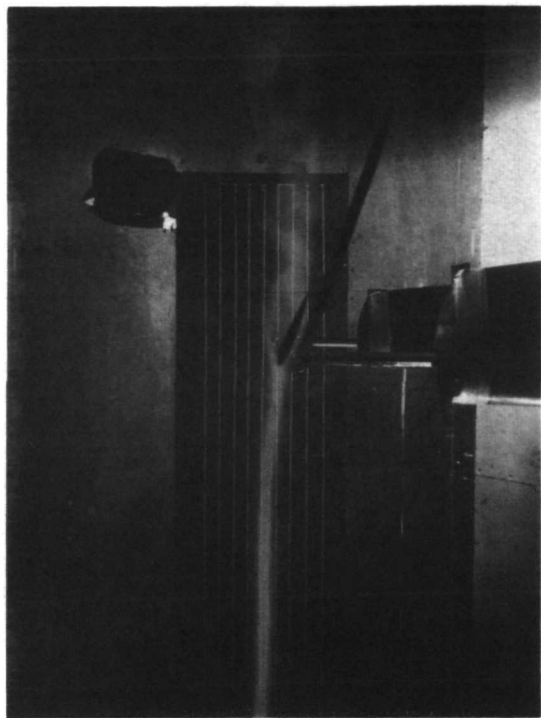
FIG. 32  $\theta_g = 8^\circ$ ,  $\lambda = 2.40$

FIG. 33  $\theta_g = 8^\circ$ ,  $\lambda = 1.60$

PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



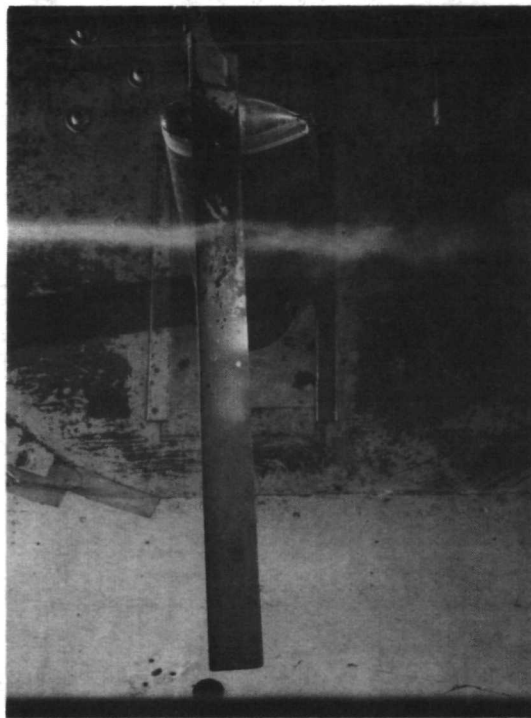
Side View



Side View



Plan View

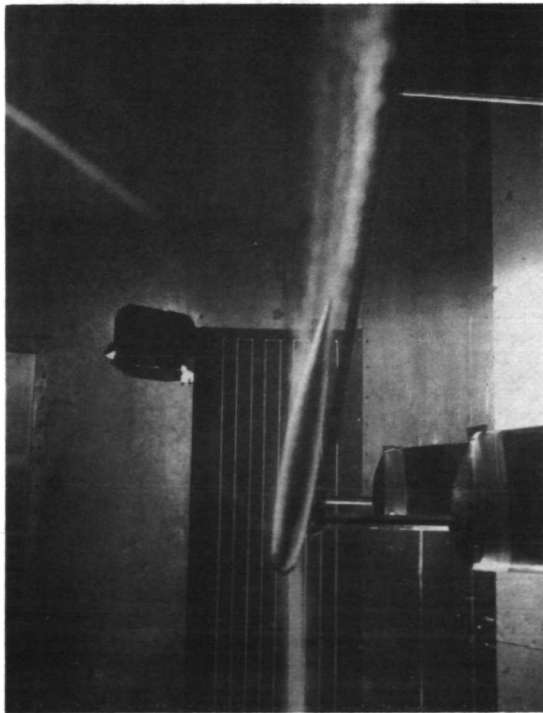


Plan View

FIG. 34  $\theta_g = 8^\circ$ ,  $\lambda = 1.00$

FIG. 35  $\theta_g = 2^\circ$ ,  $\lambda = 4.80$

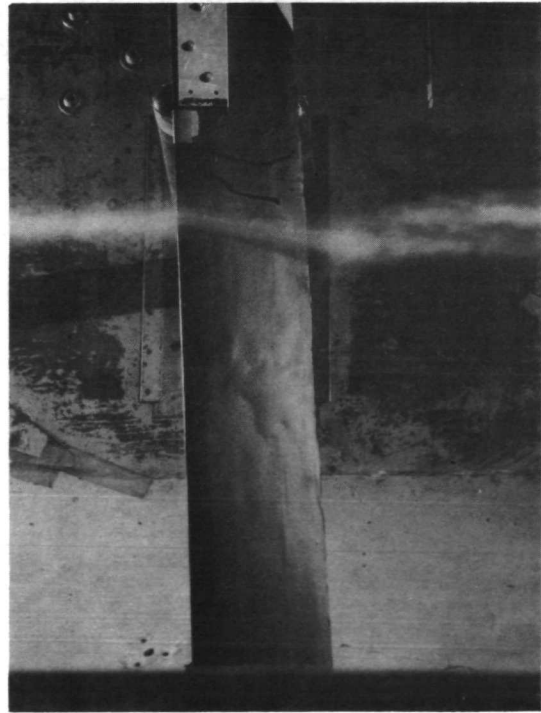
PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL



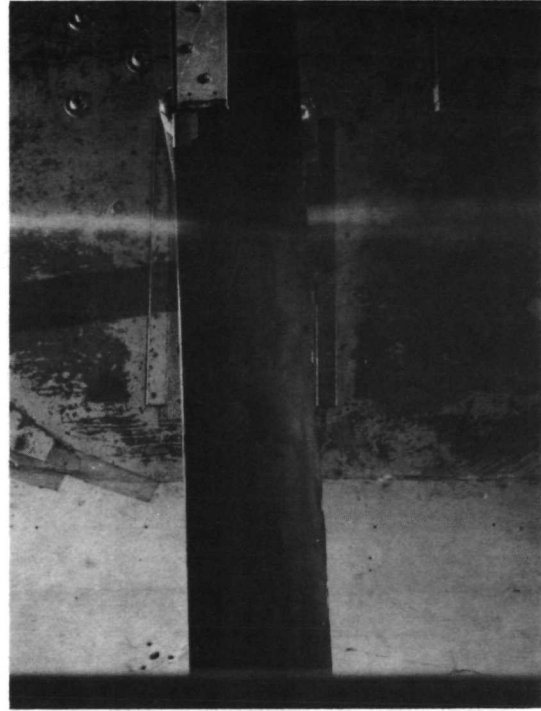
Side View



Side View



Plan View



Plan View

FIG. 36  $\theta_g = 2^\circ$ ,  $\lambda = 3.20$

FIG. 37  $\theta_g = 2^\circ$ ,  $\lambda = 1.50$

PHOTOGRAPHS OF THE TRAILING VORTEX INTERSECTING A SECOND AIRFOIL

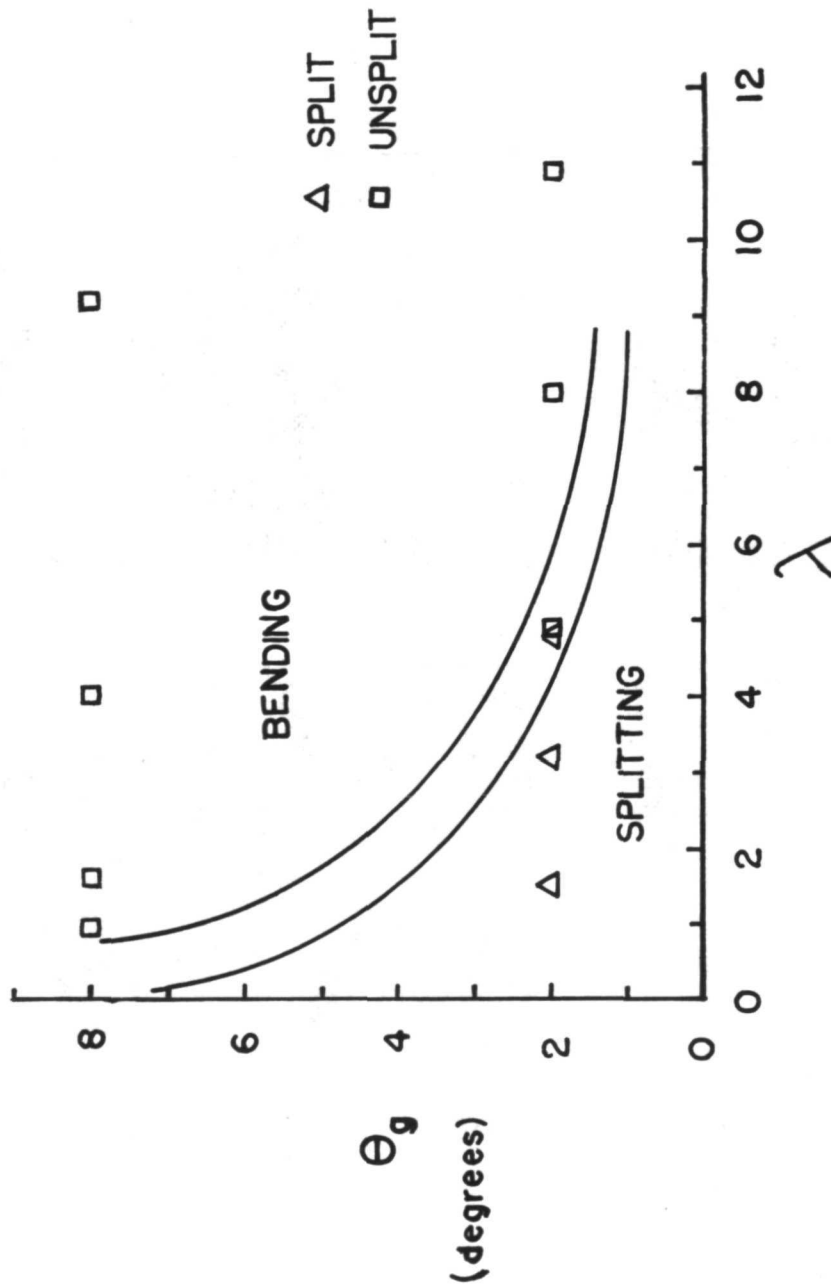


FIG. 38 FIGURE SHOWING THE APPROXIMATE REGIONS WHERE THE SPLITTING AND BENDING MODES CAN BE EXPECTED

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|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |  |                                                                             |                       |
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| d.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |  |                                                                             |                       |
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| 13. ABSTRACT<br><p>This investigation deals with the qualitative responses of a trailing vortex core to changes in its convective velocity produced in two different ways, (a) by injection of air into the vortex core and (b) by the flow field of a lifting surface in the path of the core. Flow pictures of the vortex core and vorticity measurements in the core show that an axial momentum injection of approximately 35% of the total wing drag alters the vortex structure and behavior quite drastically by effectively inducing a more rapid dispersion of the vorticity in the core. The data indicates that the phenomenon is governed by the rate of injection of the momentum rather than the mass flow rate as reported recently by Rinehart (Ref. 1). There also seems to be an optimum rate of injection beyond which increased injection does not bring about equally significant changes in the vortex core. Flow patterns of the region of interaction between the flow field of a lifting surface and the vortex core show two modes of vortex response; (a) the vortex core bends, following the streamline shape until it intercepts the wake of the wing where it is abruptly dispersed, or (b) the vortex core may be sliced into two smaller vortices when the vortex hits the leading edge of the wing.</p> |  |                                                                             |                       |

|     |                                                              |        |    |        |    |        |    |
|-----|--------------------------------------------------------------|--------|----|--------|----|--------|----|
| 14. | KEY WORDS                                                    | LINK A |    | LINK B |    | LINK C |    |
|     |                                                              | ROLE   | WT | ROLE   | WT | ROLE   | WT |
|     | Tip Blowing<br>Vortex Response<br>Vortex-Airfoil Interaction |        |    |        |    |        |    |