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DEPARTMENT OF MECHANICAL ENGINEERING TECHNOLOGY
SCHOOL OF ENGINEERING
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA

COMPUTATION OF DESIGN PARAMETERS AND VISUALIZATION OF GOERTLER VORTICES

By

Alok K. Verma, Principal Investigator

Final Report
For the period February 16, 1983 to February 15, 1984

Prepared for the
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23665

Under
Research Grant NAG-1-340
John R. Dagenhart, Technical Monitor
TAD-Airfoil Aerodynamics Branch

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Submitted by the
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COMPUTATION OF DESIGN PARAMETERS AND VISUALIZATION OF GOERTLER VORTICES

By

Alok K. Verma*

I. INTRODUCTION

Instabilities commonly known as Goertler vortices are found in the flow over a concave surface. These instabilities which are in the form of counter rotating, streamwise vortices (fig. 1) indirectly affect transition by interacting with another type of instability, known as Tollemien Schlichting waves (refs. 1 and 2). The interaction of these two types of instabilities leads to oscillation of boundary layer in a spanwise direction which ultimately leads to transition.

Goertler type instabilities are critical in cases of supercritical airfoils which have regions of concave curvature on the lower surface. A comprehensive theory of a Goertler type instability over a curved surface was presented by the author and co-authored by Dr. N. M. El-Hady. (See refs. 3 and 4). This theory presented a methodical way of calculating the most unstable wave number for both subsonic and sonic speeds. It also took into account the effect of suction and cooling.

Based on the results obtained in the above work, the present analysis offers a method for calculating the growth rate of the Goertler type disturbances over a given airfoil.

Earlier work in visualization of Goertler vortices was done at incompressible speeds. Gregory and Walker (ref. 5) were the first to observe traces of these vortices by using a china-clay technique, followed by

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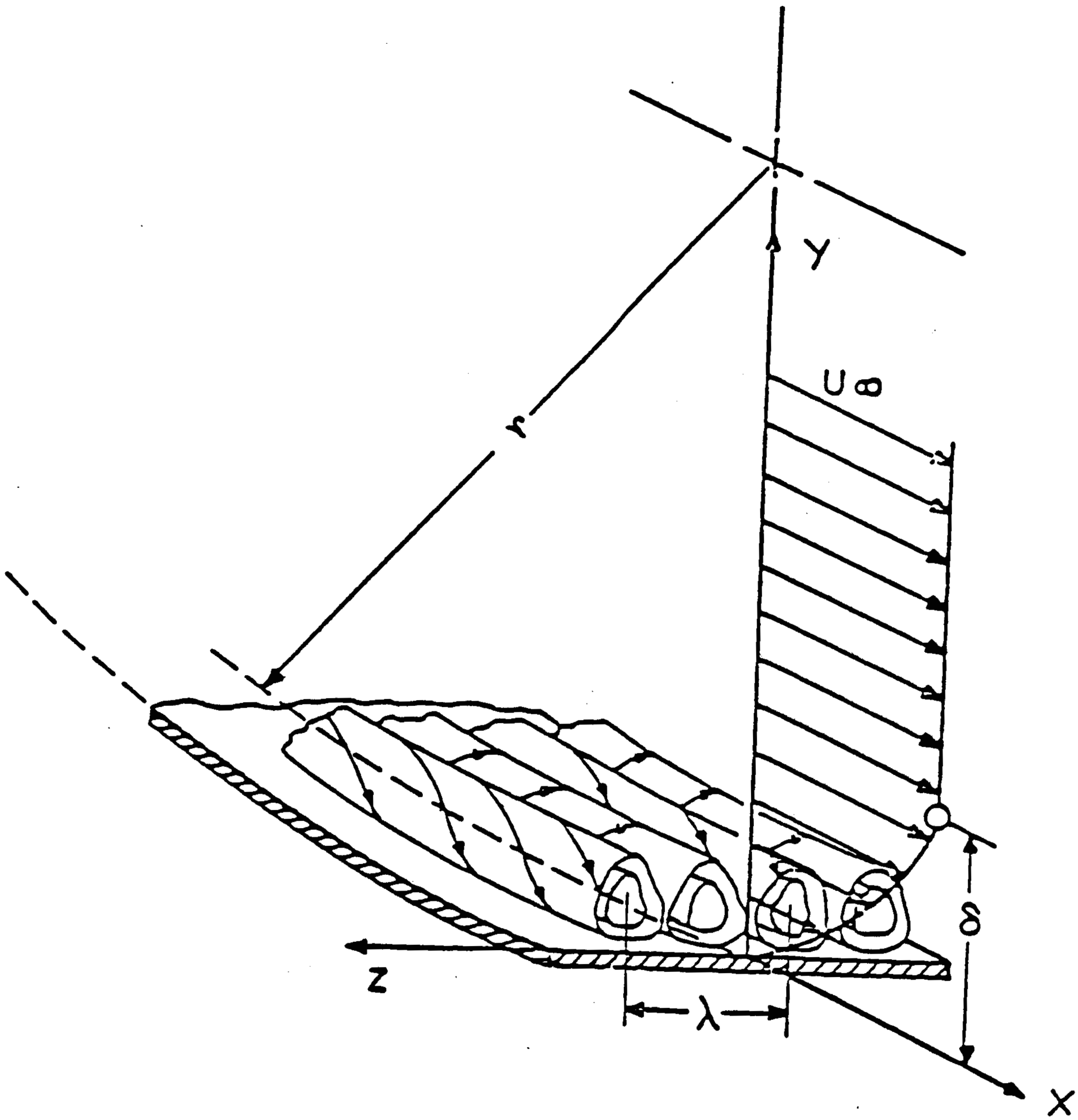

Figure 1. Goertler vortices in a flow along a concave wall.

Aihara (ref. 6), Tani and Sagakami (ref. 7) using colored liquids and smoke threads, and Aihara (ref. 8) and Tani (ref. 9) using hot wire measurements. Wortman (ref. 2) used the tellurium method to visualize these vortices in a water tunnel. Bippes (ref. 10) presented detailed observations of these vortices using the hydrogen bubble technique. At compressible speeds, evidence of the vortex like disturbances has been observed by Persen (ref. 11) and Ginoux (ref. 12) in quasi two-dimensional flows in regions of separated flow reattachments. Zakkay and Calarese (ref. 13) observed the presence of these vortices in a hypersonic turbulent boundary layer over an oxisymmetric configuration with adverse pressure gradient. In their experiments in two Mach 5 nozzles, Beckwith and Holley (ref. 14) showed by using oil flow patterns that these vortices persisted to the nozzle exit.

Section II discusses the method for analysis of an airfoil regarding Goertler instability.

Section III presents the effort made toward visualization of Goertler vortices using smoke.

II. COMPUTATION OF DESIGN PARAMETERS

A computer code was presented in ref. 3 and 4 for analysis of boundary layer stability. This program used the boundary layer profile over a flat surface as the input for the disturbance equation. The disturbance equation was solved using a variable step size integrator based on the Runga Kutta Fehlburg fifth order formulas.

Figure 2 shows the plot of Goertler number G vs wave number β as a function of growth rate σ for a value of free stream Mach number 2. Similar curves were obtained for M_∞ = 0, 1, 3, 4 and 5. The curve for $\sigma = 0$ is important since it separates the unstable region (above) from the stable region (below). The path joining the minimum of the curves represents a path most likely to be followed by growing vortices.

The present work suggests a method for applying the information available in refs. 3 and 4 to analyze the flow over the concave surface of an airfoil. This analysis can be specially helpful for comparisons with experimental results.

Given the geometry of the airfoil the values of Y_i are calculated at X_i where i can be chosen as a sufficiently large number to accurately describe the airfoil shape. Values of Reynolds number R_i and Goertler numbers G_i are calculated using a modified version of a program written by Harris and Blanchard (ref. 15).

Figure 2 shows the curves of Goertler number G versus wave number β as a function of the growth rate for Mach number 2.0. The value of critical Goertler number (value corresponding to the minimum of curves) is obtained from similar curves and plotted as a function of wave number in figure 3 for Mach numbers 0.0, 1.0, 2.0, 3.0, 4.0 and 5.0. The resulting values of the critical Goertler numbers and corresponding wave numbers are tabulated in

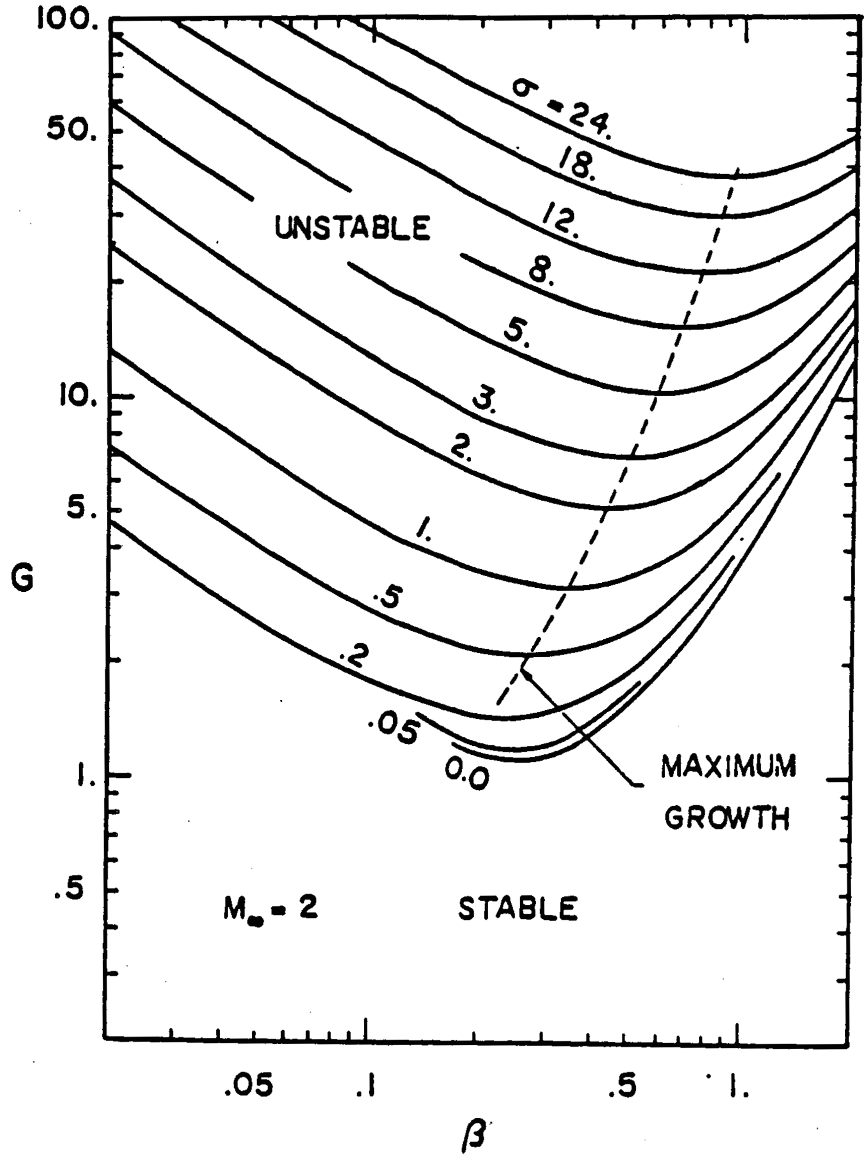

Figure 2. Contours of constant growth rates at Mach number = 2.

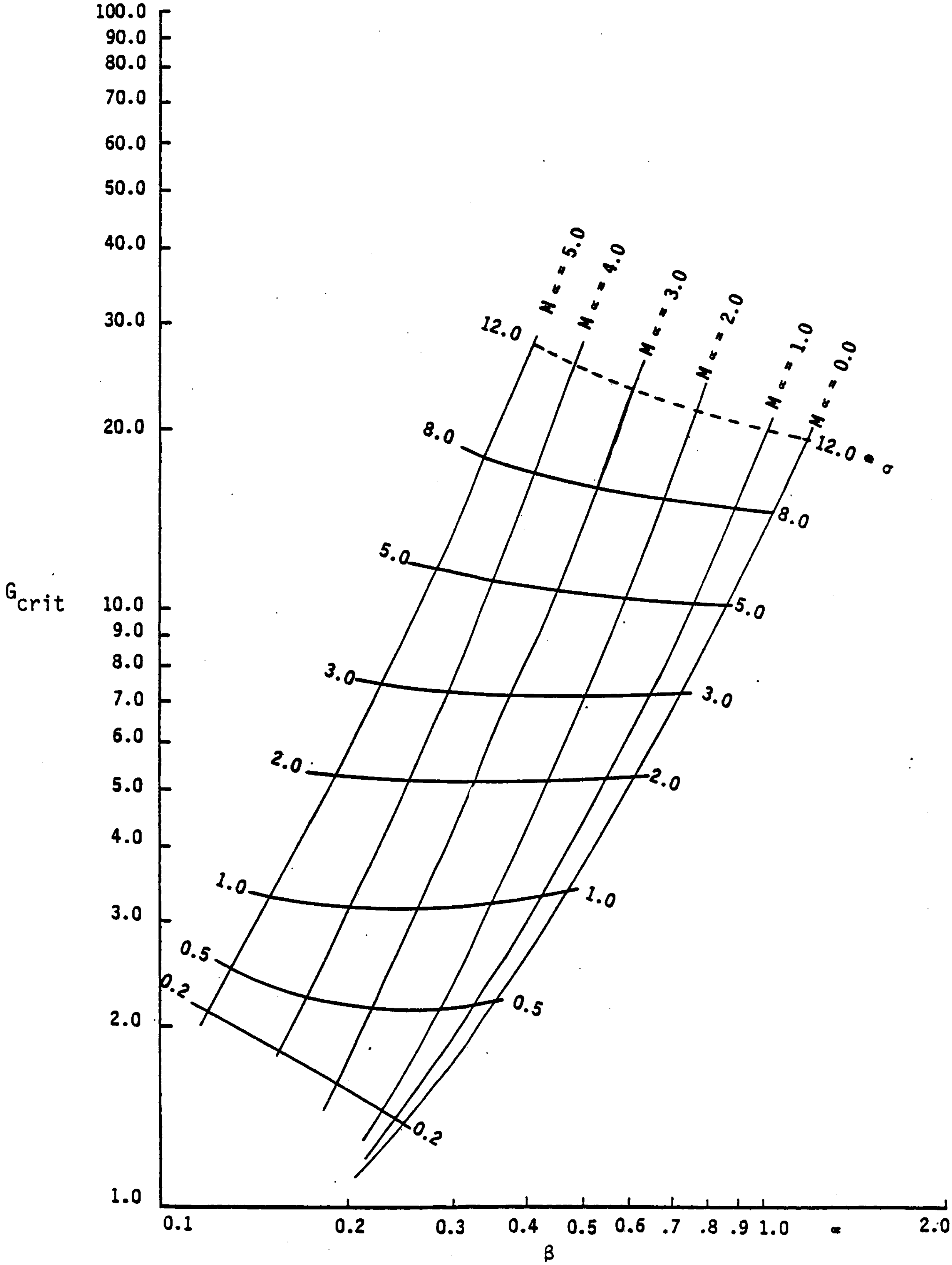

Figure 3. Curves of critical Goertler number for constant growth rates and Mach number.

tables 1 and 2, respectively. These values are used as the input value for interpolation to find out the values of the wave number β and growth rate σ for a known value of the Goertler number at a point on the surface of an airfoil.

Using these values, the amplitude ratio is calculated using

$$\ln (a/a_o) = \frac{4}{3} \int_{G_o}^{G} (\sigma/G)\, dG$$

Amplitude ratio is a direct indication of whether the flow will turn turbulent or not.

Figure 4 shows the flow chart describing the method of computation of critical Goertler number and growth rates at different stations along an airfoil surface.

The airfoil section chosen for the experimental investigation in Section II of this paper is also used here for computation of growth rates and amplitude ratio. Figure 5 shows the shape of the airfoil. Twenty-nine stations each on the top and bottom surfaces were chosen for calculation of above quantities. Coordinates of these stations are presented in table 3.

Preliminary investigations were made to find out if separation would occur on the airfoil. A program written by Eppler and Somers (ref. 16) was used for this purpose. The program plots the pressure distribution on an airfoil, and also indicates the transition and separation on both upper and lower surfaces. Several runs were made with different Mach numbers and angles of attack. Figure 6 shows the pressure distribution for Mach number 0.2 and angle of attack = 10 degrees. The location of transition and separation on the upper surface is at $x/C = 0.800$ and 0.844 respectively.

Table 1. Value of $G_{critical}$.

M_∞ \ σ	0.0	0.2	0.5	1.0	2.0	3.0	5.0	8.0	12.0
0	0.46	1.36	2.2	3.4	5.4	7.1	10.0	14.5	19.5
1	0.87	1.4	2.2	3.35	5.25	7.1	10.1	14.6	20.0
2	1.11	1.43	3.1	3.2	5.2	7.1	10.4	15.4	21.5
3	1.35	1.61	2.1	3.1	5.1	7.1	11.0	16.0	21.5
4	1.63	1.82	2.25	3.12	5.2	7.3	11.2	17.2	25.5*
5	1.93	2.10	2.5	3.3	5.3	7.4	11.6	18.0	27.5*

*Approximate values obtained by extrapolation of points.

Table 2. Value of $\beta_{critical}$.

M_∞ \ σ	0.0	0.2	0.5	1.0	2.0	3.0	5.0	8.0	12.0
0	0.02*	0.25*	0.36	0.49	0.62	0.73	0.88	1.02	1.12
1	0.23	0.24*	0.33	0.43	0.55	0.64	0.76	0.88	1.02
2	0.25	0.23*	0.275	0.35	0.44	0.51	0.59	0.68	0.76
3	0.21	0.2	0.22	0.26	0.33	0.38	0.46	0.53	0.61*
4	0.16	0.155	0.175	0.20	0.255	0.30	0.36	0.42	0.49*
5	0.12	0.12	0.13	0.152	0.198	0.23	0.28	0.34	0.42*

*Approximate values obtained by extrapolation of points.

Table 3. Airfoil coordinates.

	Upper		Lower	
Station	$X_{1°}/C$	$Y_{1°}/C$	$X_{1°}/C$	$Y_{1°}/C$
1	0.0	0.0	0.0	0.0
2	0.03623	0.02900	0.03623	-0.00725
3	0.07246	0.04529	0.07246	-0.00181
4	0.10870	0.05978	0.10870	0.00362
5	0.14493	0.07246	0.14493	0.01087
6	0.18116	0.08152	0.18116	0.01630
7	0.21739	0.09420	0.21739	0.01993
8	0.25362	0.10326	0.25362	0.02355
9	0.28985	0.11232	0.28985	0.02609
10	0.32609	0.11594	0.32609	0.02899
11	0.36232	0.11957	0.36232	0.02971
12	0.39855	0.12319	0.39855	0.03224
13	0.43478	0.12319	0.43478	0.03261
14	0.47101	0.12319	0.47101	0.03261
15	0.50725	0.11957	0.50725	0.03261
16	0.54348	0.11594	0.54348	0.03261
17	0.57971	0.10870	0.57971	0.03261
18	0.61594	0.09420	0.65217	0.02971
19	0.65217	0.09420	0.65217	0.02971
20	0.68841	0.08696	0.68841	0.02754
21	0.72464	0.07790	0.72464	0.02754
22	0.76087	0.06884	0.76087	0.02536
23	0.79710	0.05978	0.79710	0.02174
24	0.83333	0.05072	0.83333	0.01449
25	0.86957	0.03986	0.86957	0.01449
26	0.90580	0.02899	0.90580	0.01087
27	0.94203	0.01993	0.94203	0.00906
28	0.97826	0.00725	0.97826	0.00362
29	1.00000	0.0	1.000	0.0

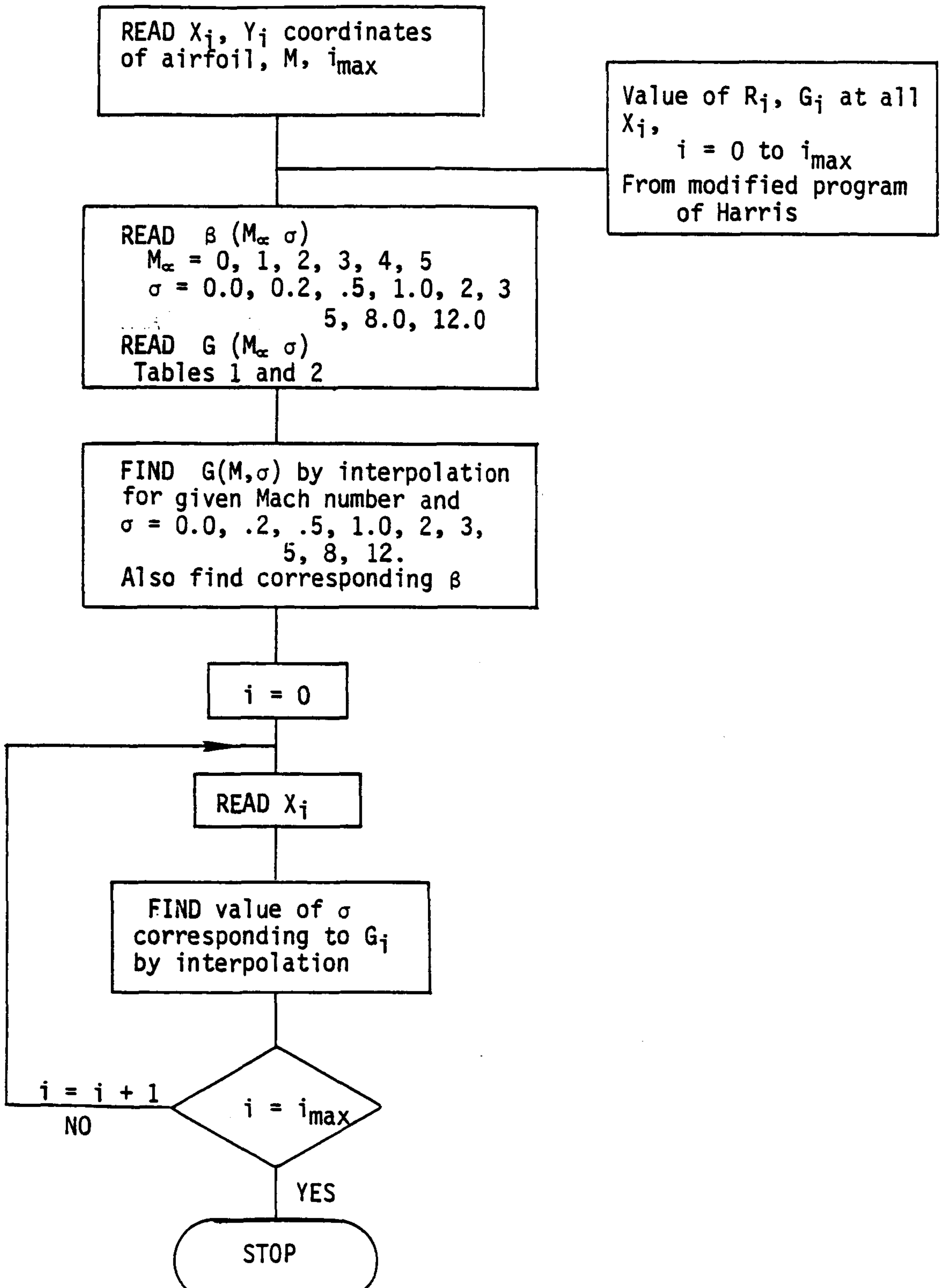

Figure 4. Flowchart for computation of critical Geortler number and growth rates along a given airfoil.

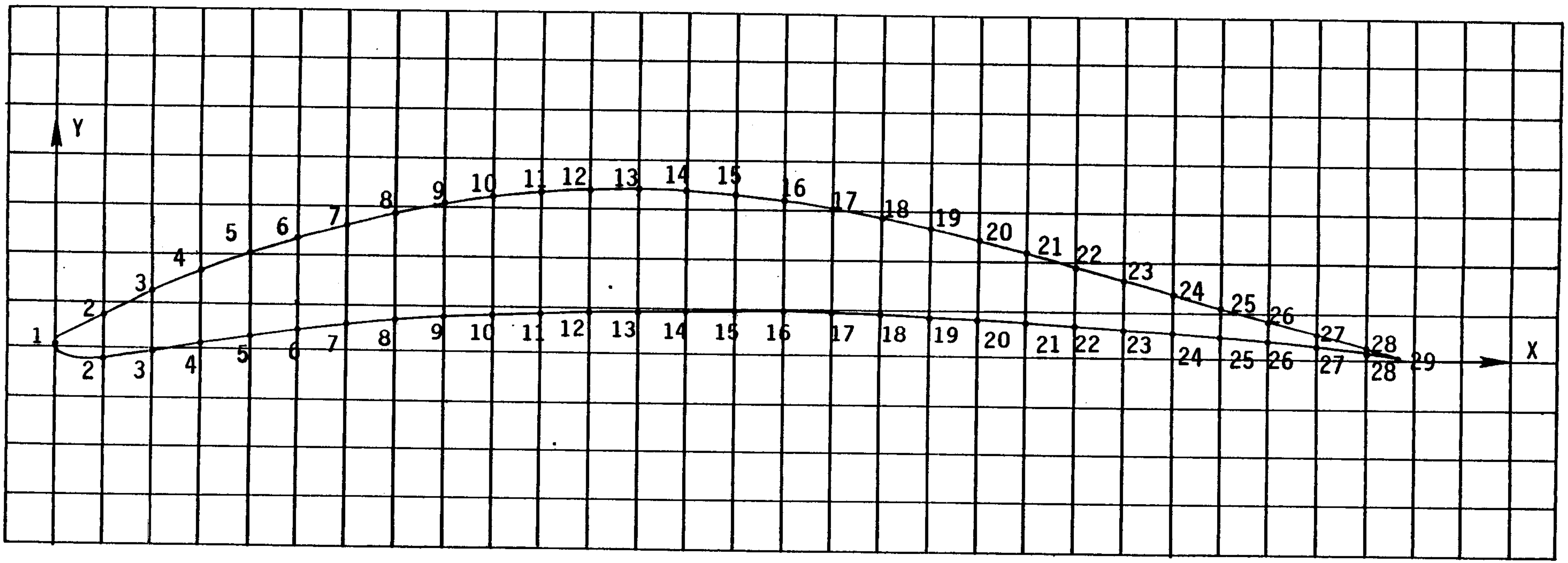

Figure 5. Airfoil used for theoretical and experimental investigation.

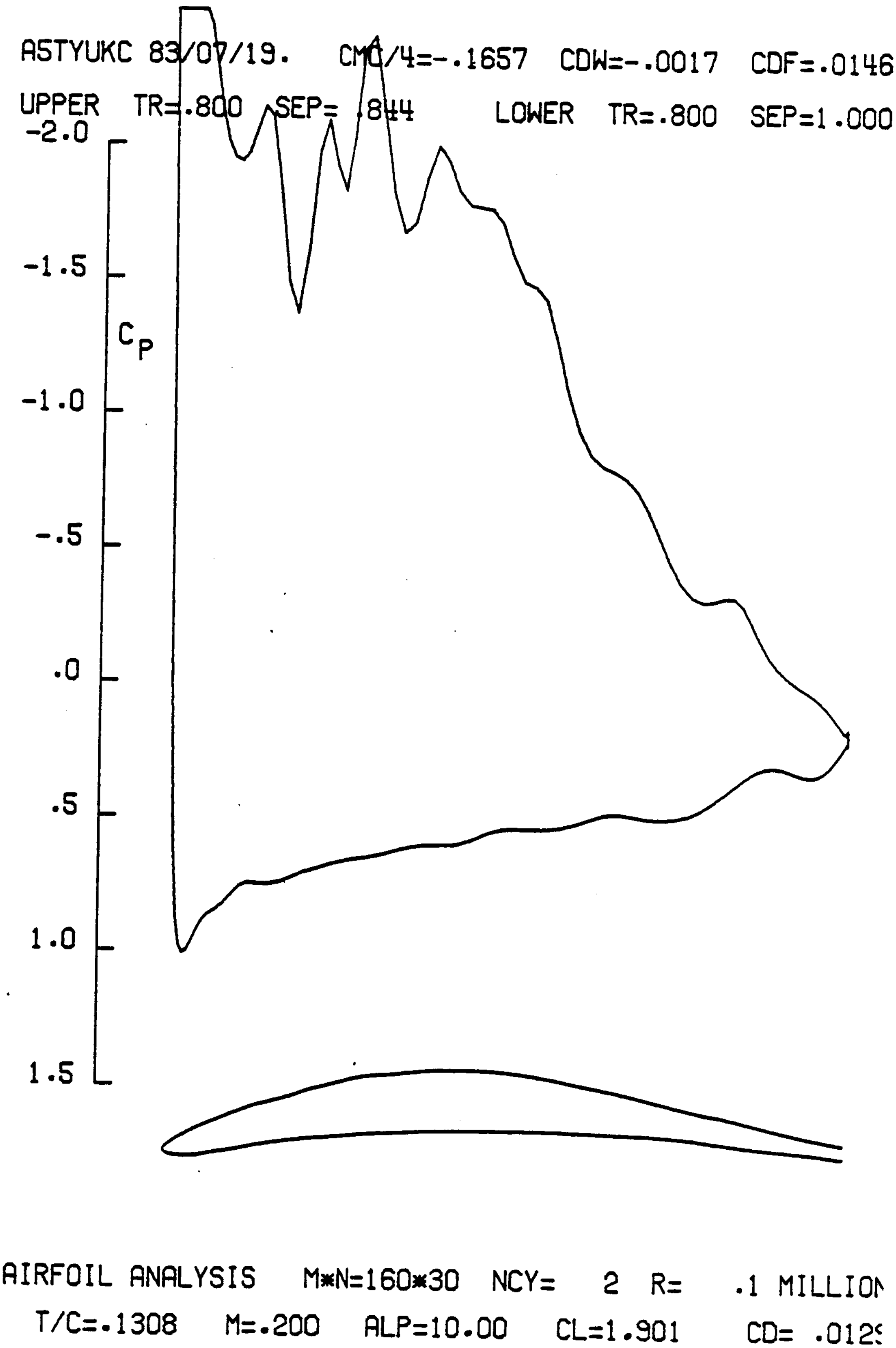

Figure 6. Pressure distribution for the airfoil.

The transition and separation on the lower surface occur at $x/C = 0.800$ and $x/C = 1.000$. It was found that the location of separation point was behind the area of concave curvature on the lower surface for the majority of cases and, therefore, the model is suitable for experimental investigation.

The oscillations in the pressure distribution on the upper surface were primarily due to the uneven surface of the airfoil.

The coordinates of the airfoil were fed through an airfoil smoothing program and subsequent pressure distributions were quite smooth. It was, however, observed that the smoothing program did not produce good results near the leading and trailing edges.

III. VISUALIZATION OF GOERTLER VORTICES

Effort toward visualization of Goertler vortices was primarily confined to the use of smoke wire. The 30.5 x 45.7 cm smoke tunnel in Building 641, at the NASA/Langley Research Center, was used for the experimental investigation. The tunnel is an open circuit, low turbulence tunnel with a maximum velocity in the range of 30-35 m/sec.

a. Design and Fabrication of Model

An airfoil shape with concave curvature was needed to study the visualization. There were two primary considerations in the design of the airfoil. First, that the curvature should be over a wider range of chord so that the vortices would have time to develop and become larger thereby facilitating their visualization. Second, there should not be any separation in the region of curvature.

Figure 4 shows the shape of the airfoil chosen. Preliminary theoretical analysis using a potential flow theory showed that for the speeds under consideration this airfoil did not have separation on the lower surface at higher angles of attack. However, for an angle of attack near zero degrees separation was predicted near the trailing edge. Figure 7 shows the construction of the model. Two templates of the airfoil shown in figure 4 were made from a hard thermoplastic material. Using the two templates foam was cut using a hot wire in the shape of an airfoil. Linerboard was glued on the foam to give it a smooth finish and to provide bending and torsional rigidity.

b. Design and Construction of Smoke Wire Apparatus

Goertler vortices are confined within the boundary layer during their

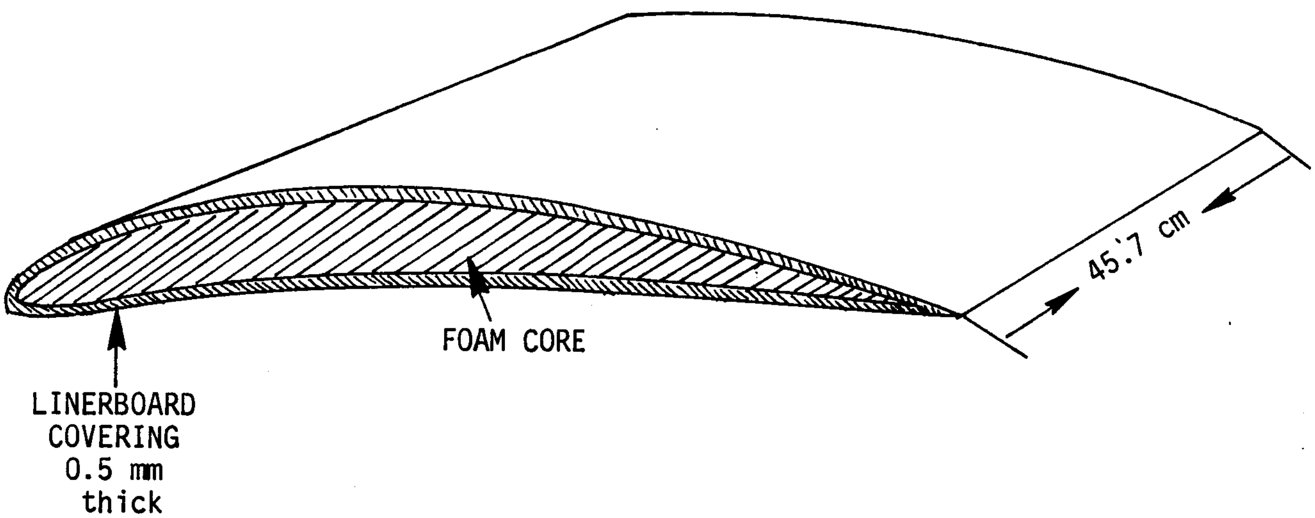

Figure 7. Construction of the model.

early stages of development, however, if their growth conditions are favorable they can grow out of the boundary layer. Thus the smoke generating device should be capable of delivering a thin sheet of smoke near or within the boundary layer. When the smoke sheet rolls with the vortices it will render them visible.

Smoke generating apparatus used for visualization is shown in figure 8. A thin wire passes horizontally through the tunnel test section over two pulleys and is connected to weights to give it tension. The wire passes through an oil reservoir. When the wire is moved over the pulleys, small drop-lets of oil adhere to the wire and create a thin sheet of smoke when the wire is heated.

The wire is connected to a dc power source through a timer with which the duration of the passage of current through the wire can be controlled. This is necessary to avoid wire burnout.

c. Experimental Setup

Visualization of the Goertler vortices can give us insight about the nature of flow over a concave surface. First, center to center, distance between the adjacent vortices gives the wavelength of these vortices which has been found to be affected by tunnel side walls. Also the wavelengths have been found in earlier experiments to remain constant in the streamwise direction. Second, the cross section of the vortices can give information about velocity distribution inside these vortices.

Figure 8 shows the experimental set up for visualization. A Hasslebad camera was used for taking instant pictures. The flash and camera were connected to a timer which controlled the current through the smoke wire. The timer had a delaying circuit built in so the camera could be triggered

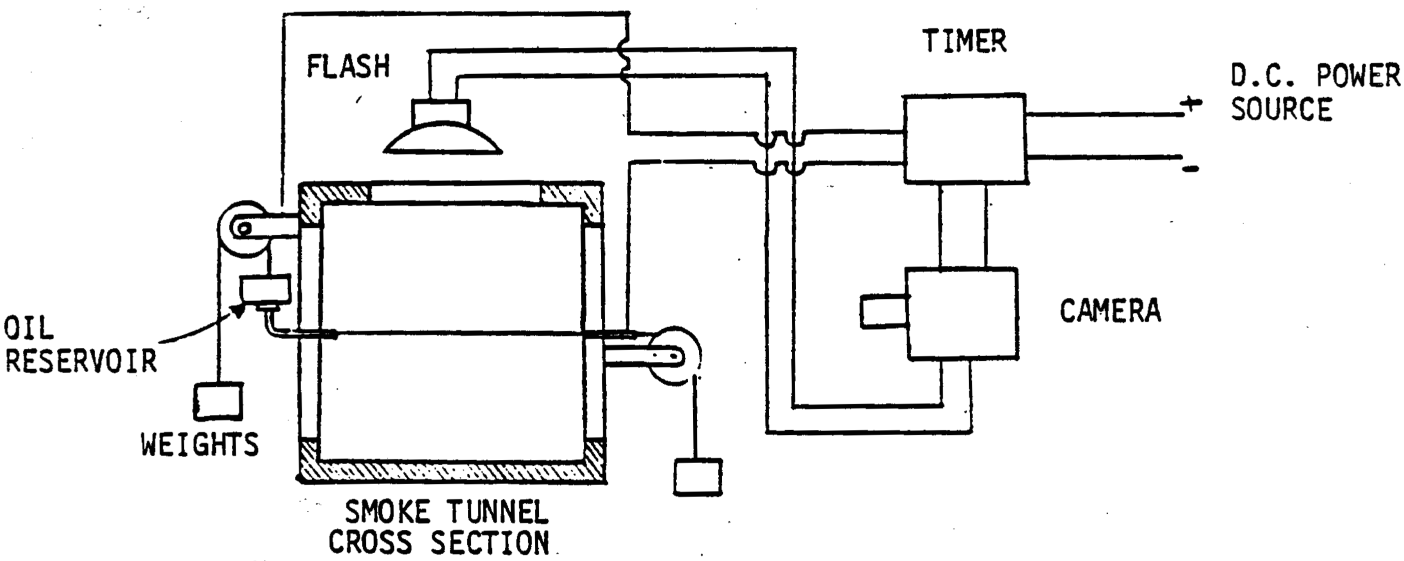

Figure 8. Smoke generating device and visualization setup.

only after certain timed intervals of heating the smoke wire.

Since the smoke wire was heated only for a fraction of a second, a smoke sheet of only a finite length was generated. The camera had to be triggered exactly at the instant when this smoke sheet was above the airfoil.

Figure 9 shows the setup for the study of the wavelength of the vortices. In this case, the camera was mounted as the top of the tunnel test section looking down at the lower surface of the wing model. The flash, with a slot in front, provided a thin sheet of light skimming the surface of the model. To avoid any reflection or diffusion of light by the model surfaces or the tunnel side walls, these surfaces were painted black. Several pictures were obtained of the flow using this setup. It was found that the smoke wires do not produce enough smoke. The tests could not be continued since the tunnel was often shut down for repairs, or was not available for testing due to previous scheduling. Over the period of this grant, the tunnel was available for this investigation for just over a week.

Figure 10 shows the setup to study the cross section of Goertler vortices using a low power laser. This setup was not used for testing due to lack of time and unavailability of the smoke tunnel.

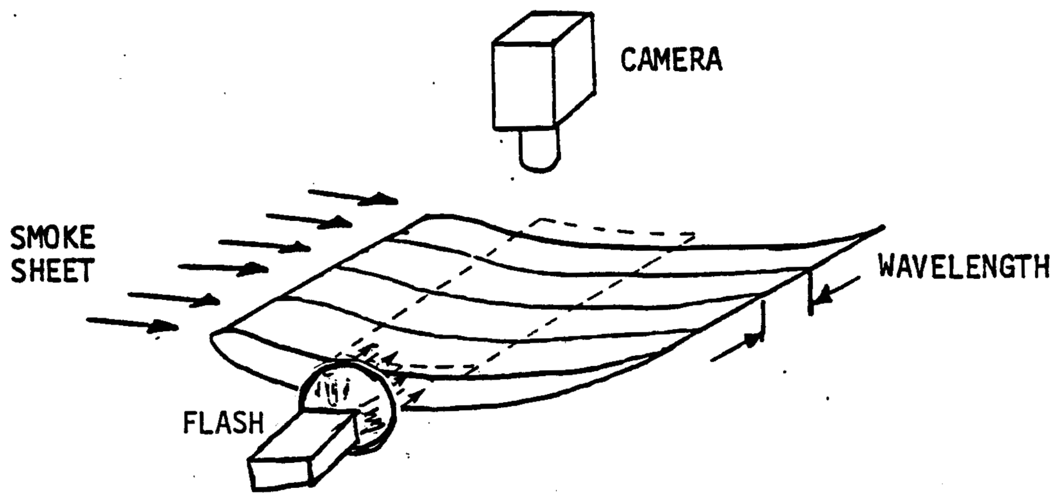

Figure 9. Experimental setup to study the wavelength.

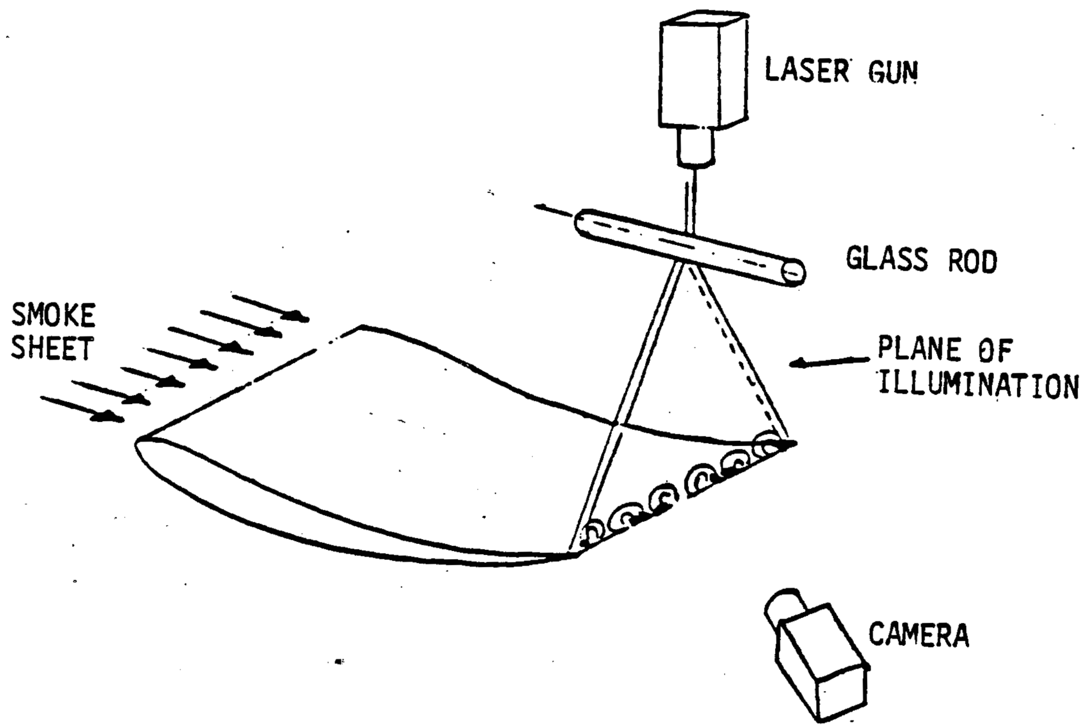

Figure 10. Experimental setup to study cross section of vortices.

IV CONCLUSION

In this work, a method for analyzing an airfoil regarding Goertler type instability has been presented. A model for the visualization of Goertler vortices was designed and fabricated. A smoke generating apparatus was made to be used in the experiment. Experiments were conducted to photograph the vortices, however, the smoke generated was not enough to bring out the vortices. Additional tests, although planned, could not be carried out for lack of time and unavailability of the smoke tunnel.

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