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REFRACTION ERRORS IN AERIAL PHOTOGRAPHY AT HIGH FLIGHT SPEEDS

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OBJECT

The object of this investigation is to determine the effect of high-speed flight upon optical resolution in aerial photography.

SUMMARY

The problem of the refraction error in aerial photography at high speeds is discussed. Computations have been initiated to determine the effects of Mach number, wall temperature, and boundary layer thickness upon the gross deviation of a light ray passing through a boundary layer. Preliminary results included in this report indicate that Metrogon type cameras will be subject to considerable wedge effect.

Experimental apparatus has been constructed and assembled to check the validity of the analytical results.

INTRODUCTION

In the analysis of the photographic system[12], it was suggested that the optical wedge effect of the boundary layer might become the "weak link" in the system at high flight speeds. Above Mach 0.5, the buildup of the compressible boundary layer forms essentially a thin wedge of air over the window surface across which the property variations become appreciable. The density and thus the refractive index changes rapidly across this wedge of air from a free stream value of N_∞ to the value N_w at the window surface. If heat is being applied for defrosting purposes, the window surface temperature is increased accordingly and the additional temperature gradient increases the refractive index variation. This laminar boundary layer grows in the direction of flow across the window in a parabolic manner; thus it appears that the wedge effect will vary from point to point along the window surface.

A survey of the literature indicates that considerable effort has been directed toward the solution of the refraction error problem in the interferometric analysis of supersonic flow.[4,9,10,17,19] In these solutions, a constant density gradient was assumed and a power series solution was assumed to hold. Weyl's analysis[19] which is probably one of the most elaborate, is directed toward the determination of the object plane for minimum refraction error. Weyl found that for his apparatus, the optimum object plane was one third of the distance in from the tunnel wall.

In the boundary layer, however, the density gradient is not usually constant; that is, it cannot be considered an arc of a great circle as has been done in the above analyses. Ladenburg and Bershader[10] studied the supersonic boundary layer and point out that the refraction error through the boundary layer is rather large.

The mathematical analysis of Liepmann[11] and the experimental work of Baskins and Hamilton[3] were found to be directly related to the photographic problem. Liepmann considered a simple plane-laminar boundary layer and a plane-turbulent boundary layer. For the laminar case, the analysis simplifies to Snell's Law for a planar boundary layer. For the turbulent boundary layer, the analysis indicate that sizable deflections occur at the higher Mach numbers. For a typical case (Mach 2.0 at sea level), the deflection ϵ was found to be 4×10^{-4} radians. Baskins and Hamilton measured changes in the intensity of a beam of light rays when a turbulent boundary layer is passed through the beam at Mach 1.43. Their data show that intensity levels changed as much as 20 percent. This indicates that considerable displacement of the image occurred. Photographic records of the image of the source

taken through the boundary layer show some flare but not as much as would be expected from the magnitude of the intensity changes observed. The photographic records show that the geometrical shape of the image of the source is not seriously altered for light of normal incidence. As a normal shock passes through the tunnel, however, a complete distortion of the image results. More recent investigators have also studied effects produced by shock waves and turbulence.

ANALYTICAL PROGRAM

Inasmuch as experimental studies are usually difficult and require expensive equipment, an analytical approach to the problem is most desirable. Once a valid method of calculation is established, a wide range of conditions can be rapidly examined. In this regard, a calculation method was proposed in an earlier report[12]. A program has been initiated to examine the magnitude of the wedge effect when each of variables, Mach number, wall to free-stream temperature ratio, boundary layer thickness, and angle of incidence, is varied independently. Calculations have been performed for the deflection to be expected as a function of angle of incidence at Mach 0.73 when the wall to free-stream temperature ratio was 1.1. The data used for the boundary layer characteristics were taken from the experimental results of Weltham and Kuhns[18]. The results of this computation are shown in Fig. 1. Further computations are being performed using the data of van Driest[16] for the boundary layer characteristics. The results of a computation for Mach 1.0 and T_w/T_∞ of 2.0 are also shown in Fig. 1. In the above analysis, the effect of shock waves has not been included.

EXPERIMENTAL PROGRAM

In conjunction with the analytical work, a program for experimental verification of the calculated information over a limited range is being undertaken. The various techniques which were examined for possible use in determining the angular deflection involved were the Mach-Zehnder interferometer[9,10,13], the Ronchi schlieren[1],the variation of the Ronchi schlieren proposed by Kraushaar[8] and the two-lens schlieren.[2,6,7,14] The interferometer and the modification of the Ronchi method provides a means for obtaining experimentally the density variation through the boundary layer as well as the boundary layer profile. The schlieren method on the other hand yields information from which the deflection angle can be obtained directly.

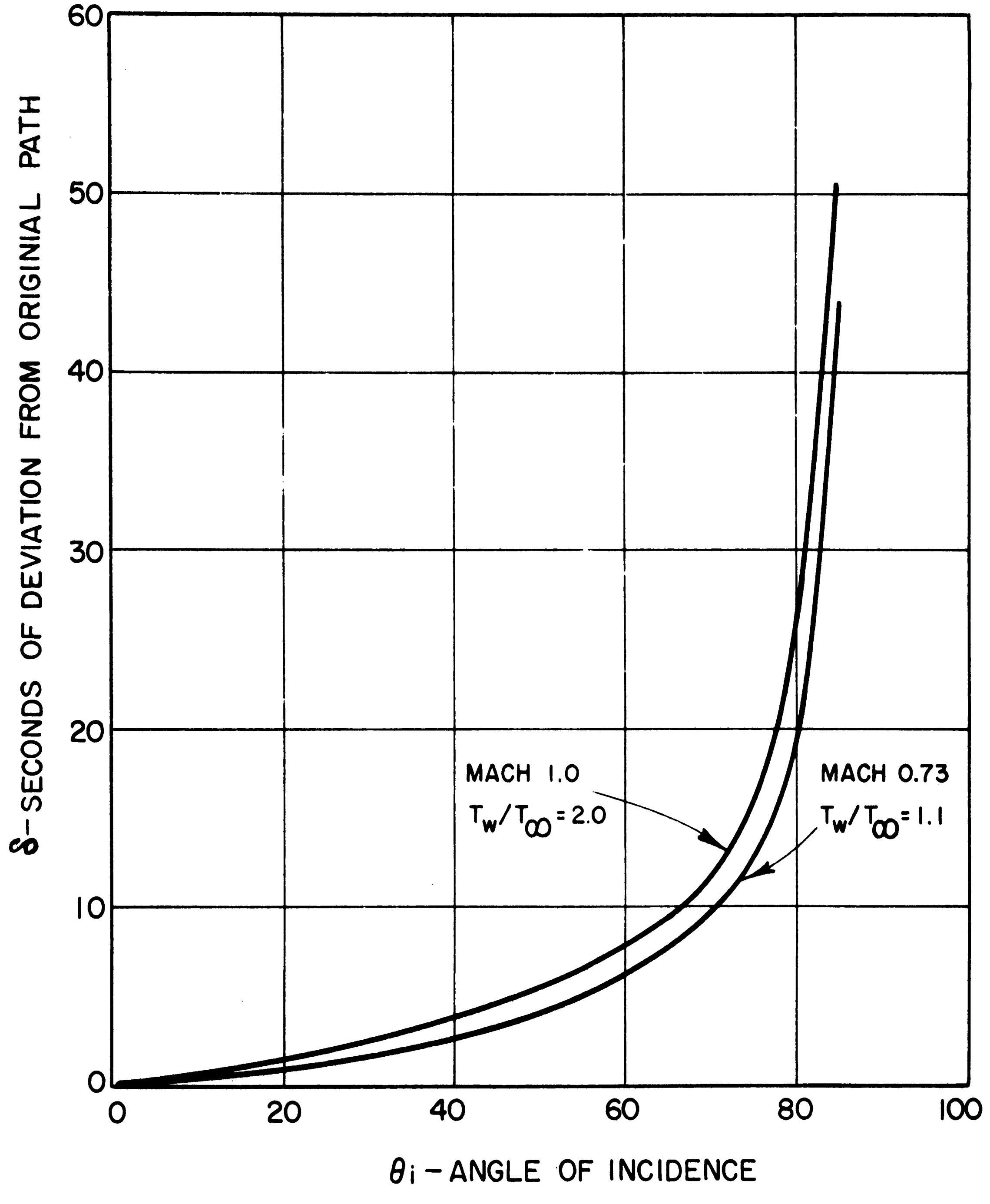


Figure 1. Angular Deviation of a Ray Passing Through a Boundary Layer at Various Mach Numbers and Wall to Free Stream Temperature Ratios.

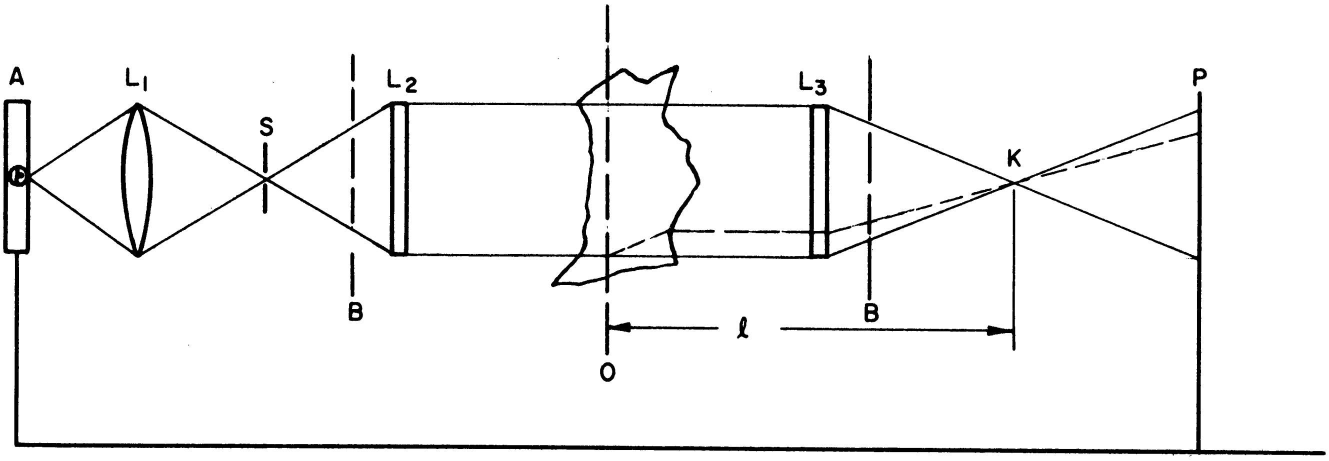
In view of the simplicity of the schlieren system and the applicability of the data which can be obtained, a small schlieren system was chosen for initial experimentation. A sketch of the apparatus is shown in Fig. 2. The system consists of a mercury vapor lamp (General Electric AH-4) for a light source (A), a condensing lens (L), a slit (S), and collimating lens (L_2), knife edge (K), a focusing lens (L_3), and a screen (P). The collimating lens is a 4.3 inch, 42 inch focal length surplus telescope objective. The sensitivity of the above system is found to be very high. Small density fluctuations caused by insertion of one's hand into the light path are readily discernable.

Light from the source A is collected and focused by the lens L_2 upon the slit S so that it is uniformly illuminated. The divergent beam of light passing through S is collimated by lens L_2 and focused upon the knife edge K which is placed parallel to the image of the source. If the knife edge is moved upward into the beam until it blocks out the image of S, no light will reach the screen P. (This presupposes high-quality lenses free of chromatic and spherical aberration and of astigmatism, and that no refraction gradients exist in the section, B-B, the test section.) Now, if some sharp disturbance is passed through B-B, some of the light rays are bent so that they pass over the knife edge K, while others are bent so that they strike the knife edge. Thus light and dark regions are observed on the screen P. In general practice, only a portion of the light is cut off initially. If a ray is bent through an angle ϵ by the disturbance so that it passes over the knife edge, the intensity of illumination on the screen may be considerably increased. If ω is the width of the slit S and ℓ is the distance from the knife edge K to the object plane O, then the proportional change in light intensity at P is given approximately by

$$\frac{\Delta I}{I} = \frac{\epsilon\omega}{\ell} \qquad (1)$$

as long as $\epsilon\omega$ is smaller than the image perpendicular to the knife edge.

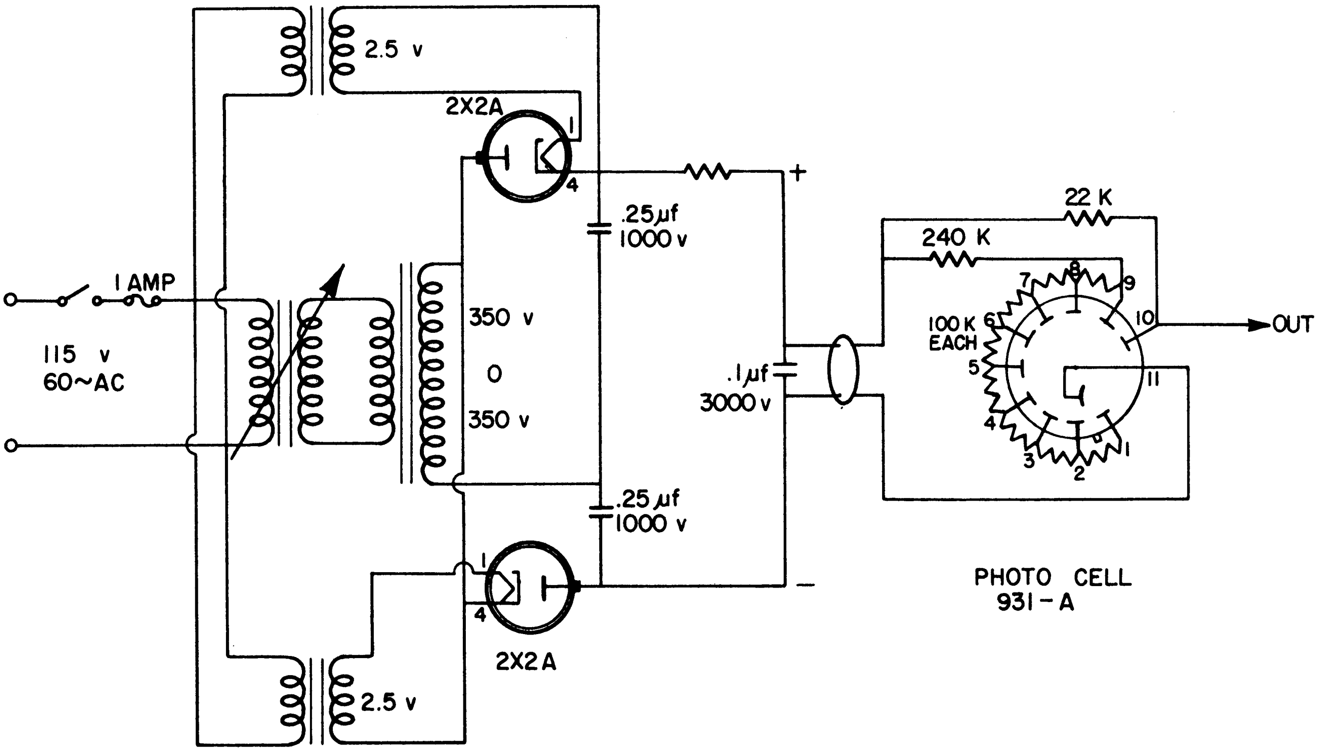
The experimental information then contains values of $\Delta I/I$ from which ϵ can be readily computed. A 929 phototube and power supply which were available were tried initially to determine the light intensity in the object field. The low level of the intensity available from the source could not be detected with the 929 tube; thus a photomultiplier tube was deemed necessary (see Fig. 3). A 931-A tube and a 0- to 1900-volt power supply was constructed from parts available. The photomultiplier tube permitted measurements of the light intensity in the plane of the screen P over a wide range of illumination. However, an initial run with this setup indicates that regulation of the power supply will probably be required since the drift of the system appears to mask the effect being measured.



Legend

A -MERCURY LAMP
L_1 -COLLECTING LENS
S -SLIT
L_2-COLLIMATING LENS
B-B-TEST SECTION
L_3-FOCUSING LENS
K -KNIFE EDGE
P -SCREEN
ℓ -DISTANCE FROM KNIFE EDGE TO DISTURBANCE

Figure 2. Two-Lens Schlieren System.



POWER SUPPLY-0 TO 1900 VOLTS AT 14 M.A.

Figure 3. Schematic Diagram for Power Supply and Photomultiplier Tube.

PROGRAM PLANNED FOR THE NEXT PERIOD

During the next period the computations are expected to be completed for wedge angle effect as a function of Mach Number, wall to free-stream temperature ratio, and boundary layer thickness for the laminar compressible boundary layer. At the same time, the experimental investigation is expected to yield some insight into the physical magnitude of the errors involved at air-flow rates near Mach 1.0.

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