THE DESIGN AND CONSTRUCTION OF A MACH INTERFEROMETER

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This is to certify that the

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THE DESIGN AND CONSTRUCTION OF A MACH INTERFEROMETER

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INTRODUCTION

The Mach interferometer often referred to as the Mach-Zehnder interferometer is a modification of the Jamin instrument. Mach and Zehnder about 1890 and Cranz about 1926 used interferometers of this type to observe and study supersonic gas flow in jets and the disturbances produced by bullets fired with supersonic velocity.

The importance of the Mach interferometer lies in the fact that the instrument when adjusted to give interference fringes is highly sensitive to changes in index of refraction of the air in any single "arm". A great advantage lies in the fact that by proper adjustments the interference pattern can be brought into focus in any plane so that fringes can be focused in the same plane with the object to be studied. The Michelson interferometer affords a well known example which by comparison shows the value of a Mach interferometer. If one examines the characteristics of the Michelson interferometer one can see immediately that the production of localized interference fringes is based on equality of the optical paths. However the light must traverse each "arm" of this instrument twice, which is a distinct disadvantage if one is interested in air density gradients and their influence on light refraction. A displacement of fringes can be produced by the addition of a thin reflecting film to the surface of one of the mirrors, but such displacement is primarily a function of distance, not gas density. As has been pointed out in order to examine density gradients in a gas the light should traverse the path in question only once. Otherwise interpretation of fringe displacement becomes almost hopeless except in the simplest cases.

In the Mach interferometer a fringe displacement is produced by introducing a gas of greater or lesser density into a portion of one of the paths; the boundary between the gases of differing densities is indicated by a fringe shift and the magnitude of the shift is directly proportional to the differences in density. Such an arrangement necessitates the use of a second optical path identical in length and in the same plane as the path to be interrupted. Of course the second path must be through a gas (air) of constant density in order that fringe shifts be produced solely by density gradients in the path to be examined.

Consider the interference pattern in a Michelson interferometer when the optical paths are identical. If both light wave fronts are reunited in one plane either a completely dark or completely bright field results. If the two mirrors are slightly turned about vertical axes the wave fronts emerge from the instrument not in the same plane but crossed in such a manner that interference fringes are produced. Close to and on either side of the intersection of the two wave fronts which marks equal optical paths, straight or localized fringes are found. Further from the axes of intersection as the distance between the wave fronts increases the fringes become curved and approach hyperbolic shapes. The straight or localized fringes must be obtained when using the Mach interferometer.

Now if monochromatic parallel light is incident on the fifty percent reflecting surface of the first plane parallel plate of a Mach interferometer, the wave front is split into transmitted and reflected wave fronts. These are each fully reflected by plane, mirrored surfaces and rejoined at a final plane parallel plate which is fifty percent reflecting. There the wave front originally transmitted is reflected and the reflected wave front is transmitted. Either vertical or horizontal interference fringes can be produced depending upon the orientation of the axes of intersection of the two wave fronts. In addition, the number of fringes in the field is directly proportional to the size of the angle between the wave fronts. It can be seen that as one of the above wave fronts passes through a gas possessing a density gradient parallel to the plane of the wave front that the portion of the light front passing through gas of lesser density traverses a medium possessing a lower index of refraction. This results in a displacement of the wave front which in turn is reflected in a shift in the fringe pattern.

A Mach interferometer was designed by R. B. Kennard[1] of the National Bureau of Standards for use in the study of temperature distribution and heat flux in air. By employing suitable relationships he readily determined isothermal lines about a heated body placed in the interferometer field.

Using the same plates as those used by Kennard, R. Ladenberg, J. Winkler, and C. VanVoorhis[2] designed a Mach interferometer which was built in the shops at the Bureau of Standards. This instrument since about 1943 has been used for the study of gas flow about objects in a free, homogeneous, supersonic, air stream.

Still more recently at the Aberdeen Proving Grounds a huge heavily-armored Mach interferometer has been constructed using plane parallel plates ten inches in diameter. This instrument is designed to operate in a vertical plane suitable for the study of characteristics of projectles in actual flight.

THE PROBLEM

The problem concerned with in the work described in this thesis was the design of a Mach interferometer and the construction of that instrument in the shop of the Physics Department of Michigan State College. No other instrument was available for examination at any time and no plans or details other than those briefly discussed by the workers mentioned above were to be had. For the most part references to interferometers of the Mach type are in German publications not available at the Michigan State College Library.

DESIGN AND CONSTRUCTION

In designing this Mach interferometer care has been taken to produce an instrument which at any future date can be adapted readily for study in any of the fields described above. It is expected that in the near future equipment will be constructed to provide a supersonic air stream which will be used in conjunction with this instrument for the study of gas flow about obstacles suspended in that stream.

One of the first questions to be answered in connection with this problem was whether two of the plane parallel plates available at Michigan State College were sufficiently well-made to transmit parallel monochromatic light without distortion. This requires that in addition to the surfaces being exactly plane parallel and being accurately flat to a twentieth of a wave length of light, the glass of which the plates were made must possess optical uniformity or in other words exact physical and chemical homogeniety. Incidently it should be noted here that all four plane parallel plates used in this instrument are known to possess surface flatness to within one twentieth of a wave length of light.

Time limitations prevented the application of a strictly quantitative test for accuracy of light transmission. Instead, a test was devised from observation of a qualitative nature and data was obtained within the limits of accuracy desired. The equipment for this test included a broad, monochromatic light source rendered approximately parallel with a collimating lens. A holder which was capable of movement on an optical bench in a plane normal to the incident light was used to hold the plates to be examined. A fixed, low-power telescope with a bi-filar micrometer eyepiece was placed in such a manner that the light normally incident on the plate was transmitted directly to the scope.

The four plates were aluminized on each side with a fifty percent aluminum coating vaporized from a tungsten filament in a high vacuum of at least 10^{-4} millimeters of mercury. These plates when observed in transmitted light essentially form Fabry-Perot interferometer plates which have optical glass separating the plane, mirrored surfaces instead of air as in the conventional set-up. The plane, mirrored surfaces of a Fabry-Perot interferometer are brought into a parallel adjustment by observing the fringes which form a symetrical, unchanging, bulls-eye interference pattern of successive light and dark rings. The change from a bright center to a dark center requires an optical path change of one-half wave length, representing two complete traversals of the medium between the surfaces. Such a change indicates a change in separation in the surfaces by a quarter of a wave length.

Since it was expected that the two plates to be used for transmitted light would possess transmission accuracy greater than a quarter of a wave length, the test concerned with above was limited to measurement of relative changes in the diameter of the first bright ring as observed through the scope. From this data estimates of the change in optical path length through various portions of the plates could be made. A comparison of these measured diameters with the maximum diameter of the bright ring just before the dark center appeared gave a sufficiently quantitative basis for the determination of overall accuracy of light transmission. It was found that after allowing sufficient time for temperatures to stablize repeat readings on diameters could be obtained within three to five percent at a particular point which was observed at the beginning and checked at the end of the thirty to forty minute reading period.

On the basis of the above observations the plate marked "120" was found to be accurate to one twentieth of a wave length in transmitted light and the plate marked "121" was found to be accurate to one seventieth of a wave length. These measurements cannot be regarded as reliable to better than ten percent, but since the plates were considered sufficiently accurate the Mach interferometer was constructed. The two plane parallel plates used for totally reflecting mirrors distorted the transmitted light to such an extent that no attempt was made to determine any value for transmission characteristics.

The generalized layout of a Mach interferometer involves a square or rectangular optical path plan employing a forty-five degree angle of incidence on the first fifty percent reflecting surface and a forty-five degree angle of reflection from the second fifty percent reflecting surface. A suitable monochromatic light source must be collimated to give parallel light incident on the first plate at forty-five degrees. A camera can be placed to record the interference pattern which by appropriate adjustments is brought into focus in any portion of the optical path.

This particular instrument was designed to use a thirty degree angle of incidence (see diagram) in order to obtain a wider useable field than is possible with a forty-five degree set-up. This means an increase in field width from .707 to .866 of the plate width. To insure stability of the instrument the base plate was made of half-inch brass approximately ten inches wide and fifteen inches long, supported at three points. All moving parts were machined to close tolerances with not more than a thousandth of an inch clearance, and the instrument was designed so that such clearances would be further restricted to reduce undesireable motion to a minimum. Sufficiently strong springs were used on adjustments to assure positive reverse movement and to reduce lost motion in threads. Examination of the instrument will show that each adjustment is so designed that by a simple process of resetting, the springs can be kept in their best operating range. Provision has also been made for removal of any lateral motion which might develop in the two movable base mounts. Three point suspension has been provided for all four plane parallel plates to minimize strain and distortion in the glass. Each plate mount has been provided with completely independent motions, one about a vertical axis and another about a horizontal axis, both axes being through the center of the plate. In addition to these motions both mounts for the totally reflecting plates are designed with a sliding motion for adjusting differences in path length; controlled movements of eight millionths of an inch or approximately one third of a wave length of green light are possible for this path change.

The two plates used for transmitted light have a fifty percent reflecting aluminum coat on the "front" while the fully reflecting plates have at least an eighty percent reflecting aluminum coat. These figures, although an approximation, are probably accurate to within ten percent. The dimensions of the transmission plates are 8 X 6 X 1 (cm.), while the reflecting plates are 10 X 6 X 1 (cm.).

ADJUSTMENT

Adjustment of this instrument to produce the desired fringes is probably the most exacting to be found in the field of interferometry. The following procedure has been used on this particular instrument and although other methods and operations could be substituted this method should be entirely satisfactory. The first step is to align the instrument for a thirty degree angle of incidence. This is accomplished by placing an object level with the center-line of the plates at a point such that an angle of sixty degrees is formed between the line from the object to the center of the first plate and the line between centers of the first two plates. A duplicate set-up should be provided to assist in obtaining a thirty degree angle of reflection from the last plate. Proper manipulation of the appropriate adjusting screws for both optical paths will give overlapping images through the centers of the plates. To improve this alignment use a sodium vapor lamp collimated to produce parallel light incident on the first plate at a thirty degree angle. With the object used above placed in the parallel light rays a discrepancy will probably be observed in the overlapping images of the object and the outlines of the source. For the adjustment of vertical lines the micrometer of the first plate and the micrometer of the plate receiving light from the first plate by transmission may be used alternately to bring into superposition first the images of the source and then the images of the object. When these motions are in the proper sense successive adjustments will soon bring both object and light source into alignment at the same time. A similar procedure is followed to bring the horizontal lines into proper alignment. The interference fringes should appear as alignment becomes more nearly perfect.

The second step is to obtain white light fringes which appear when exact equality of the optical paths has been reached. These are especially difficult to find. Place a common light bulb in front of the sodium vapor lamp to give a source which provides both the sodium doublet and white light in the field. It will be noted that as the optical path of one arm is lengthened or shortened, fringes from the sodium doublet appear sharper due to superposition of the 5890 A and 5896 A lines and fainter when otherwise. White light fringes, when they appear, will be found with the sharper sodium doublet fringes. However, only an experienced observer can identify the white light fringes in the presence of the sodium light. A traversal of the field where the sharper fringes are found should be made with the sodium vapor lamp masked out temporarily. The use of a transmission diffraction grating will help in locating the white light fringes when they are in the immediate vicinity of the field being examined. Incidentally, the fringes may show a slight curvature. This can be readily corrected by shifting the source slightly to increase or decrease the angle of incidence.

When the white light fringes have been located, the adjustment is completed with the installation of a monochromatic light source. A low-pressure mercury arc with filters to eliminate all but the 5461 A line was used to obtain the second photograph of interference fringes. The first photograph shows white light fringes in focus in the plane of the pointed object and was made with a three hundred watt light bulb as a source. Variations in uniformity of the source intensity results in general light and dark areas in the photographs, hence these sources are not considered ideal for photographic work.

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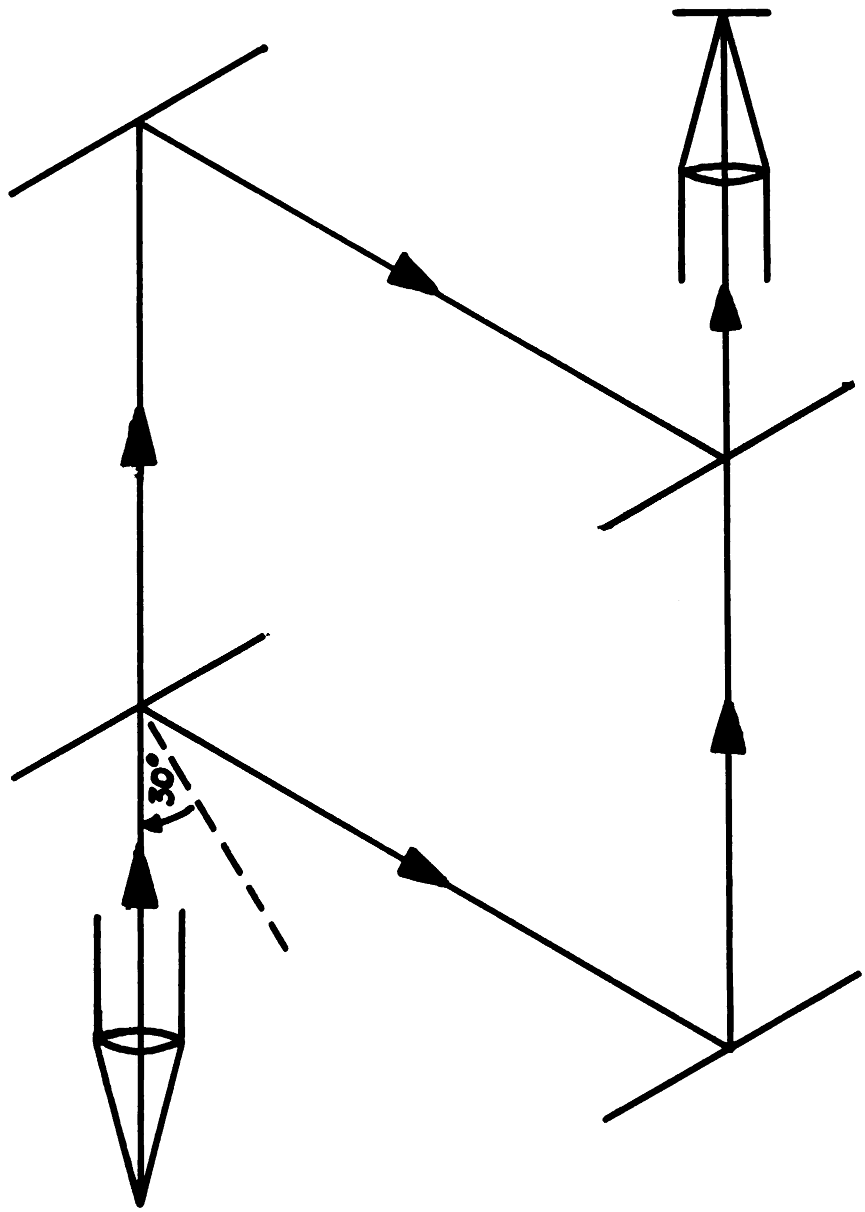
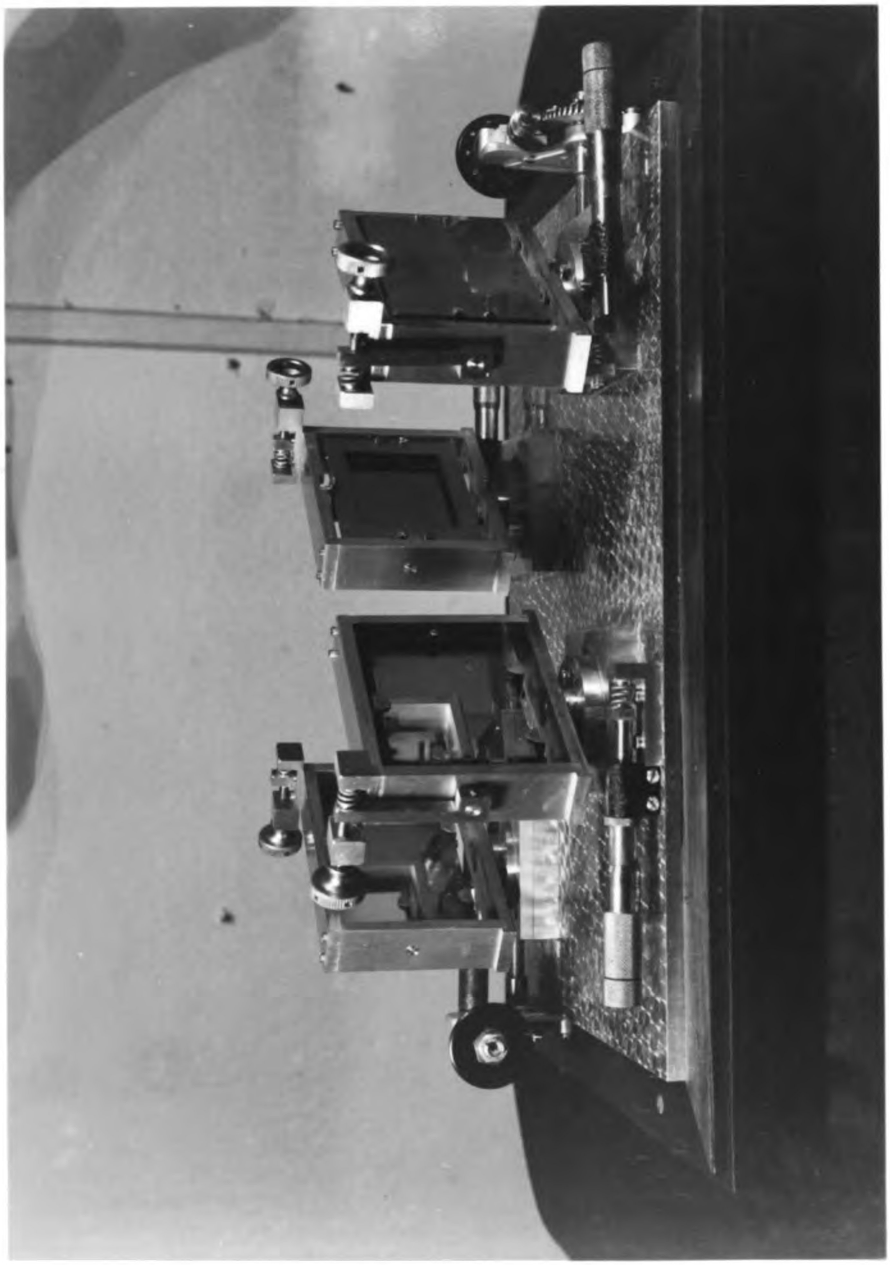
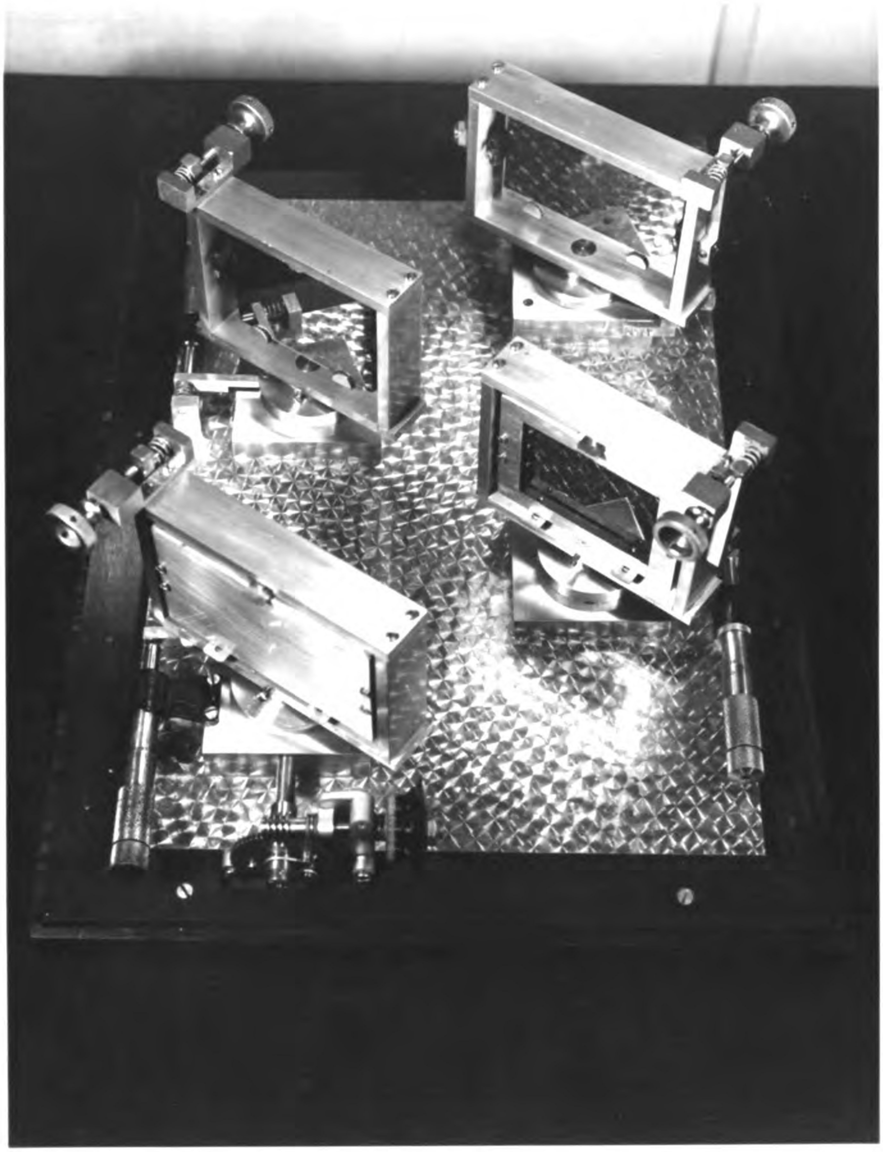


DIAGRAM OF OPTICAL PATHS

Mach Interferometer with Dust Cover



Side View



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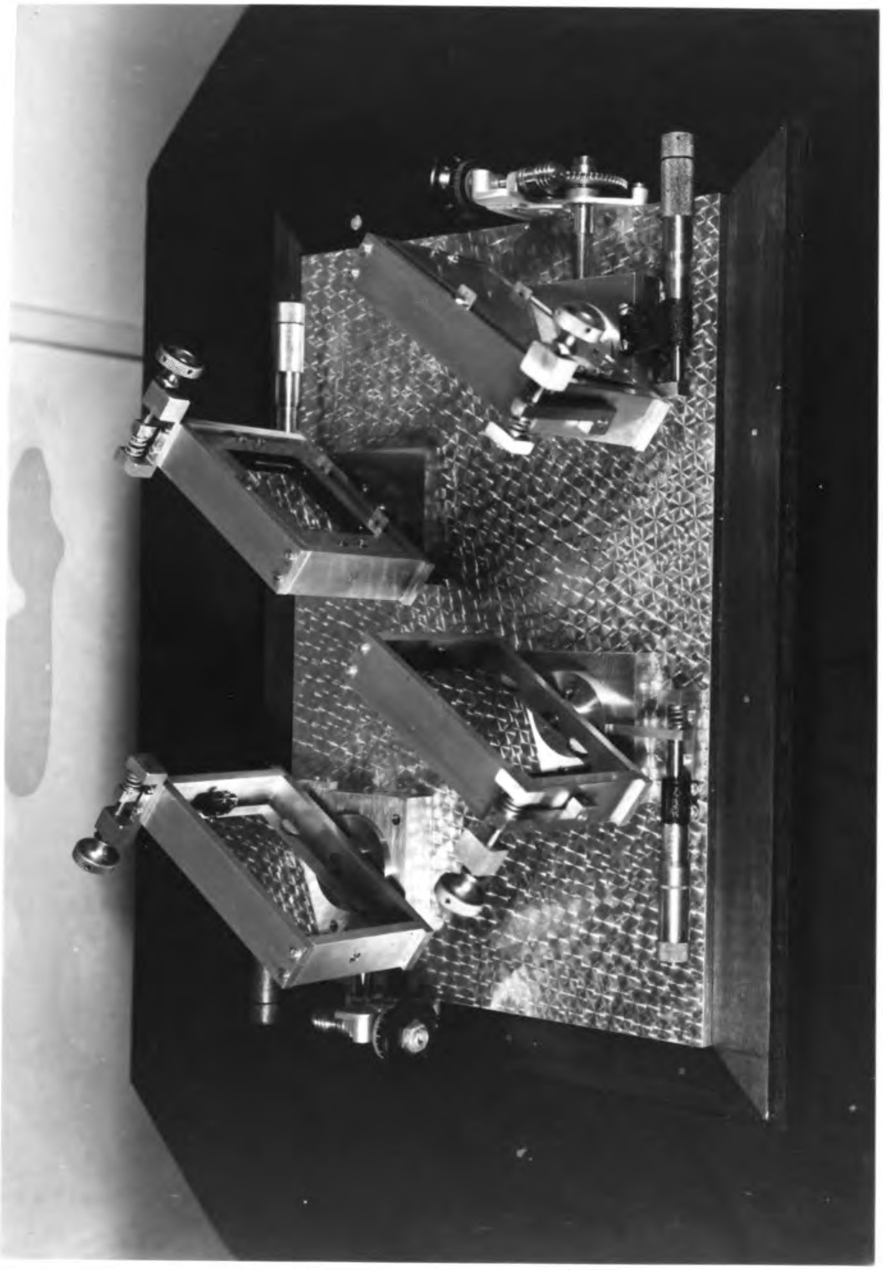
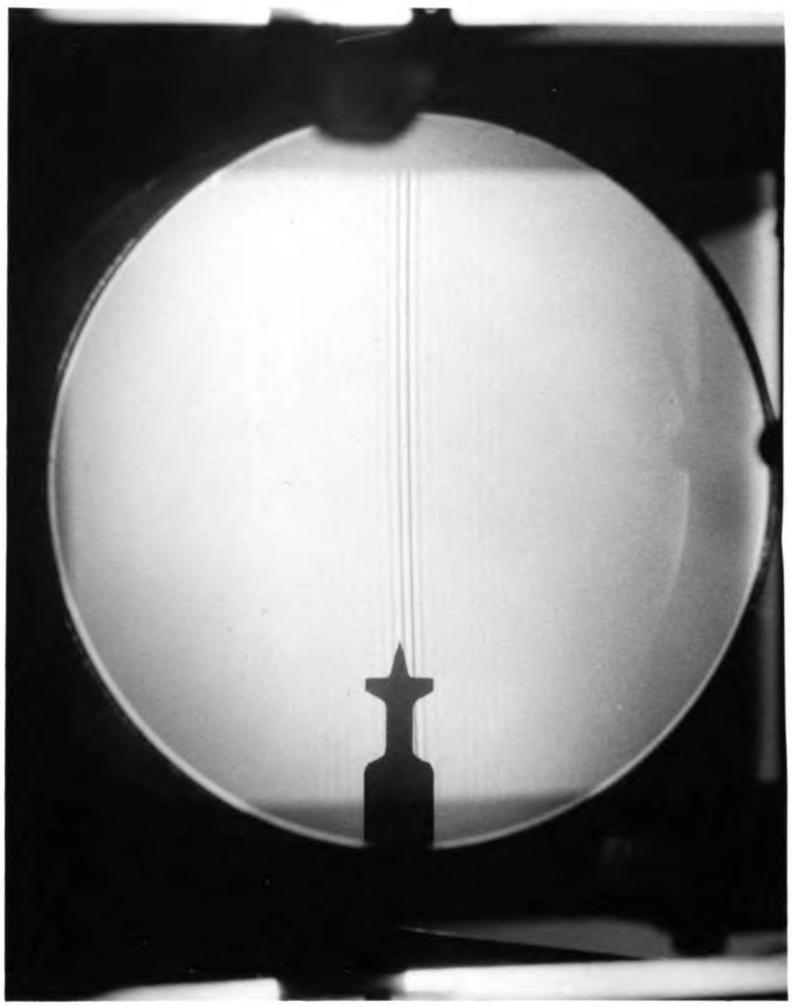
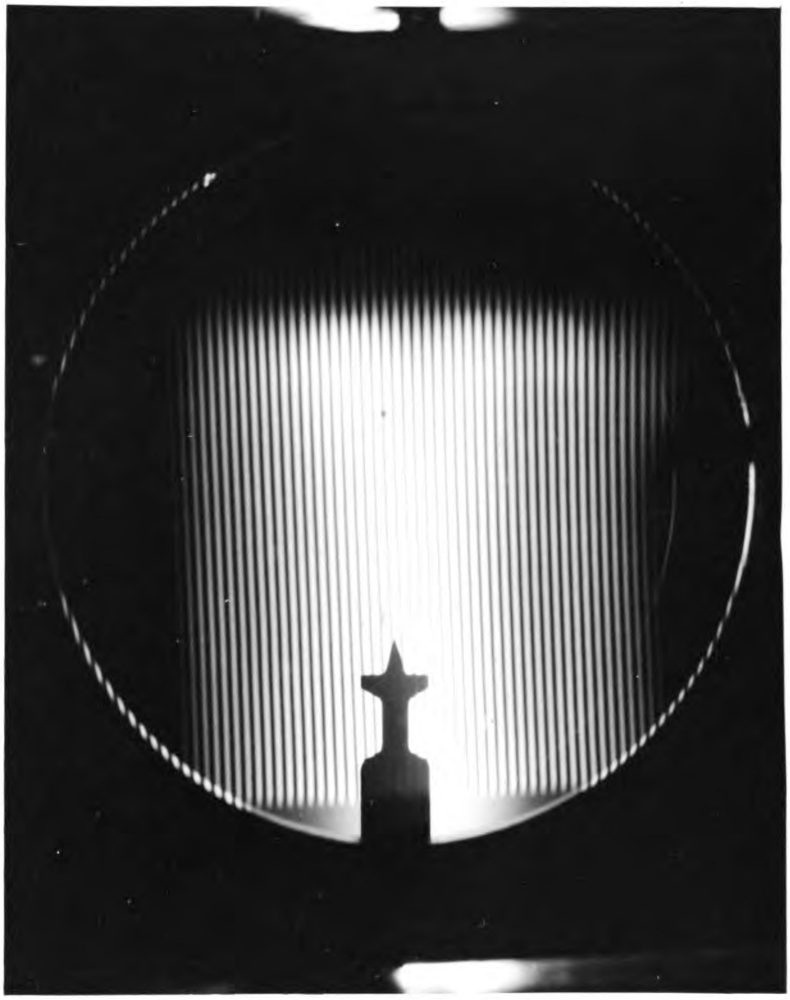


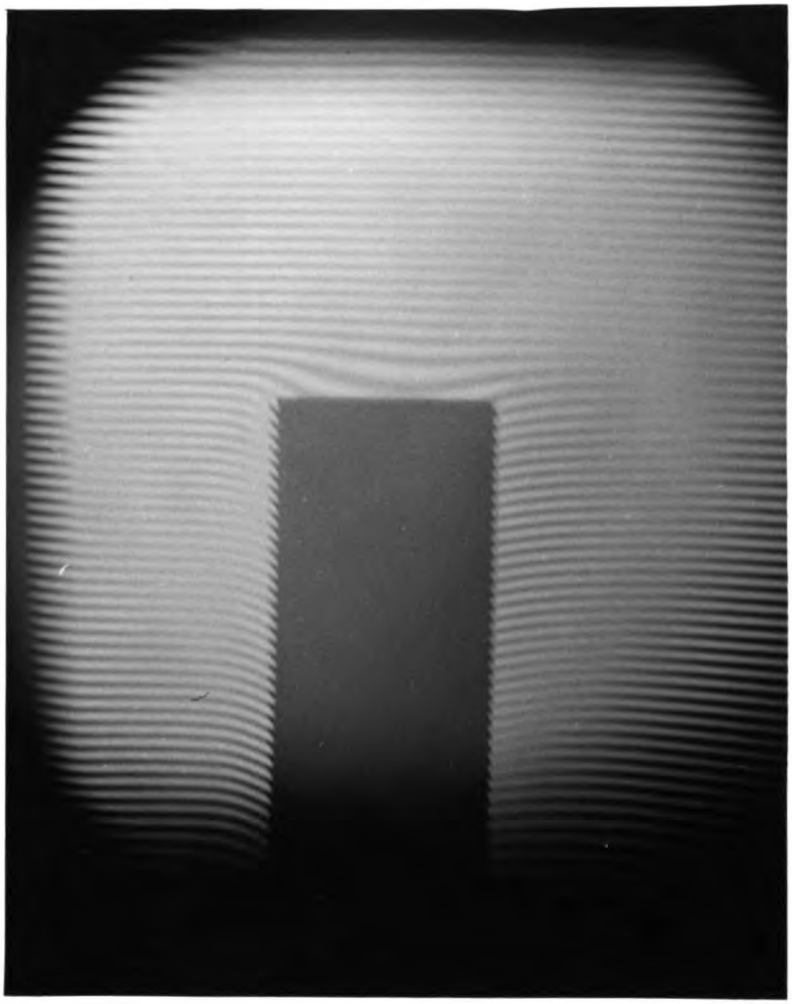
Top View



White Light Fringes



Fringes with Monochromatic Light (5461 A)



Fringe Displacement Produced by a Heated Rod