Two–Beam Interferometer Using a Laser

U. GRIGULL AND H. ROTTENKOLBER

Institut für Technische Thermodynamik der Technischen Hochschule München, Germany

(Received 26 August 1966)

A new interferometer is described which is simple to set up, adjust, and operate. The instrument retains the desired properties of conventional Mach–Zehnder or Michelson interferometers. The application of the laser interferometer ranges from wind-tunnel research to quality control of surfaces.

INDEX HEADINGS: Interferometer; Laser.

IT is well known that a two-beam interferometer is convenient for precise measurement. In the use of this instrument the phase difference between a test beam and a reference beam is determined. This phase difference can be caused by an inhomogenity of refractive index, a so-called schliere, or by a difference in the geometrical path length of a light beam.

The first interferometer, in a modern sense, was devised by Michelson[1] in 1882. In this type of interferometer, the test beam and the reference beam are made coincident by reflection. Therefore this type is suited for measuring surface finish. For tests of transparent objects, the light beam passes through the test region twice. Today the best-known type of interferometer for research is that described by Mach[2] in 1891 and, independently, by Zehnder[3] in the same year. In this type of interferometer, now known as the Mach–Zehnder interferometer, the beam passes only once through a transparent object.

These interferometers impose high demands on the mechanical precision of the optical components as well as on the experimental skill of the operators. Because of this, interferometers have only slowly been adopted by research workers. These problems of precision and adjustment have given rise to an extensive literature on this subject, such as Hansen,[4] Schardin,[5] Kinder,[6]

and Hannes,[7] among others. Although almost eighty years old, the Mach–Zehnder interferometer is still undergoing development. Johnstone and Smith,[8] for instance, give a thorough discussion of construction details and Gebhart and Knowles[9] describe a new piezoelectric adjustment system for the mirrors.

The possibilities of applying two-beam interference instruments are very broad. Thus, since Mach, this instrument has been used for the study of problems in fluid mechanics and high-speed flow. During and after the end of the second world war, interferometry has been used for research in wind tunnels, such as Zobel[10] and Wood.[11] Although there have been some new developments in the use of interference methods by Erdmann[12] and Kraushaar,[13] they have not been successful in obtaining results comparable to those achieved with Mach–Zehnder interferometers.

Kennard[14] in 1932 was the first to apply interferometeric methods in studies of heat transfer. Later a Mach–Zehnder instrument was used by Eckert, Soehngen, and Schneider[15] in a comprehensive study

[1] A. A. Michelson, Phil. Mag. 12, 236 (1882).
[2] L. Mach, *Mitteilung im Anzeiger der Wiener Akademie* (5 Nov. 1891); Z. Instrumentenk. 12, 89 (1892).
[3] L. Zehnder, Z. Instrumentenk. 11, 275 (1891).

[4] G. Hansen, Z. tekhn. Physik. 12, 436 (1931).
[5] H. Schardin, Z. Instrumentenk. 53, 396, 424 (1933).
[6] W. Kinder, Optik 1, 413 (1946).
[7] H. Hannes, Optik 12, 17 (1955).
[8] R. K. M. Johnstone and W. Smith, J. Sci. Instr. 42, 231 (1965).
[9] B. Gebhart and C. P. Knowles, Rev. Sci. Instr. 37, 12 (1966).
[10] Th. Zobel, *Luftfahrtforschung* (Forsch. Ber. 1938), p. 1008.
[11] G. P. Wood, Agardograph 23, 123 (1956).
[12] S. F. Erdmann, Appl. Sci. Res. 32, 149 (1951).
[13] R. Kraushaar, J. Opt. Soc. Am. 40, 480 (1950).
[14] R. B. Kennard, J. Res. Natl. Bur. Std. 8, 787 (1932).
[15] E. R. G. Eckert, E. Soehngen, and P. J. Schneider, in *50 Jahre Grenzschichtforschung*, H. Görtler and W. Tollmien, Eds. (Fried. Vieweg u. Sohn, Braunschweig, 1954), p. 407.

of free convection. The optical properties of laminar thermal boundary layers were investigated by Grigull[16] in 1963. Rottenkolber[17] has presented new and simple interferometric methods, applied to the study of thermal boundary layers. The free convection in horizontal annuli was treated by Grigull and Hauf[18] using the Mach–Zehnder interferometer.

Instruments of the Michelson type are used to control surface finish and for determining the quality of optical components. The difficulties and cost of this instrument increase considerably as the diameter of the field of view is enlarged. Therefore, for testing surface finish, interference microscopy[19] is almost exclusively used. For testing the flatness of surfaces, the multiple-beam method is commonly employed, as discussed by Schorsch[20] and Kinder[21]. Instruments for production control of optical components usually have a larger field of view.

The interferometric method is increasingly preferred for other problems. Weinberg[22] gave a synopsis of methods used to measure the properties of flames. Andelfinger and co-workers[23] measure the density of the electrons in a hydrogen plasma with the Mach–Zehnder interferometer.

The advantages of the interferometric method have led to its increasing adoption for measurement in recent years. Unfortunately the operator must have considerable experience because operation of conventional instruments is still complicated in spite of some mechanical simplifications.

We have developed an interferometer which can be operated by persons not experienced in the use of optical instruments. The advantages of both the Michelson and the Mach–Zehnder interferometers have been combined. This new instrument has been made possible by employing the unique coherence properties of lasers. The high quality of commercial lasers has made this development convenient, practical, and of reasonable cost.

The new laser interferometer can be arranged in two fundamental ways, one with the light-beam arrangement similar to the Mach–Zehnder interferometer, and the other with the light beams arranged similar to the Michelson interferometer. The laser interferometer differs from conventional interferometers by the com-

pletely different treatment of the test beam and of the reference beam. This is possible because laser light has a high degree of coherence. For the same reason, the interferometer can also be used without any special apparatus for light-beam compensation.

LASER INTERFEROMETER OF THE MACH–ZEHNDER TYPE

The main feature of this arrangement is that the reference beam is spread, so that its angular subtense equals that of the test beam, prior to recombination of the two beams. In Fig. 1, this beam arrangement is shown. The collimated laser beam, a few millimeters diameter, is split into two beams, the test beam and the reference beam, by the beam splitter T_1. The test beam is brought to the desired diameter of the field of view by the short-focal-length objective O_1 and the telescopic lens L_1. The test object M is put into the collimated test beam. The image of the test object M is formed by the second telescopic lens L_2 and by the objective KO in the plane BM. The reference beam is brought into angular coincidence with the test beam by the objective O_2 and is recombined with the test beam at the beam splitter T_2. The mirrors S_1 and S_2 serve only to redirect the light.

The advantage of the laser interferometer compared with a conventional interferometer used with a conventional light source, such as a Hg lamp, may be seen by reference to Fig. 1. The mirrors and beam splitters in this arrangement can be made quite small, a few millimeters in diameter. The required optical quality (flatness better than a tenth of a wavelength), can be achieved relatively easily with such small dimensions. The laser La, the beam splitter T_1, the objective O_2, the beam splitter T_2, and the telescopic lens L_2 can be combined in one unit and the telescopic lens L_1, the mirrors S_1 and S_2, and the objective O_1 can be combined in a second unit, as indicated in Fig. 1 by the dotted lines. The optical elements shown in Fig. 1 can be arranged in another way so that the two beams have essentially the same length. This is important for observations of extremely short duration (10^{-9} sec),
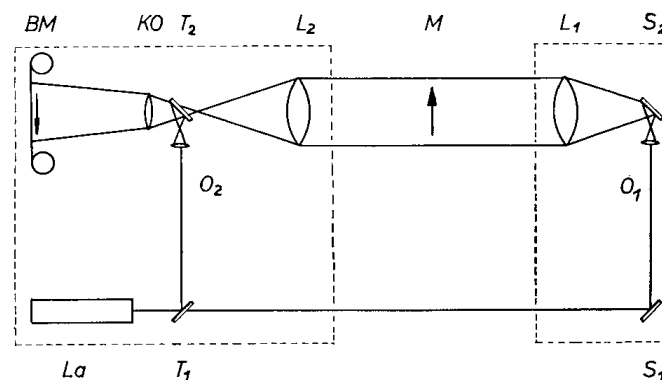
[16] U. Grigull, Intern. J. Heat Mass Transfer 6, 669 (1963).

[17] H. Rottenkolber, Fortschr.-Ber., VDI-Zeitschr., Ser. 6, No. 8 (1965).

[18] U. Grigull and W. Hauf, in *Proceedings of the Third International Heat Transfer Conference* (Am. Inst. of Chem. Engrs., New York, 1966), Vol. II, p. 182.

[19] W. Krug and E. Lau, Die Technik 3, 122 (1951).

[20] H. Schorsch, in *Optik und Feinmechanik in Einzeldarstellungen*, Dr. N. Günther, Ed. (Wiss. Verlagsgesellschaft, Stuttgart, 1958), Vol. 1.

[21] W. Kinder, *Der Ebenheitsprüfer und die Interferenzgeräte zur Oberflächenprüfung*. (Zeiss-Inf. Nr. 58, Oberkochen. 1965)

[22] F. J. Weinberg, *Optics of Flames* (Butterworth, London, 1963).

[23] C. Andelfinger, U. Igenbergs, and W. von Jaskowsky, in *Proceedings of the Sixth International Conference on High-Speed Photography*, edited by J. G. A. de Graaf and P. Tegelaar (H. D. Tjeenk Willink u. Zoon N. V., Haarlem, 1963), p. 328.

Fig. 1. Light-beam arrangement in a laser interferometer of Mach–Zehnder type.

because the distance traversed by the light during this time is about 300 mm and the wave trains of the two beams must sufficiently overlap. With either arrangement, the units of Fig. 1 must be free from vibrations. The two units may be arranged at arbitrary distances apart, thus accommodating test objects of various sizes. This is in contrast to the usual Mach–Zehnder interferometer in which the length of the object is limited to about one meter. The arrangement of the camera KO and BM is not critical.

Adjustment of the instrument is simple. Initially, the real and the virtual focal planes of the telescopic lens L_2 and the objective O_2 must coincide. This is accomplished by observing the interference fringes in the plane BM. If the two focal planes do not coincide, concentric circular interference fringes are observed. By moving the objective O_2 along the optical axis the concentric fringes can be made straight. By rotating and tilting one of the mirrors S_1 or S_2 or one of the beam splitters T_1 or T_2, one of the straight fringes can be made to spread over the entire field. This is most advantageously done by adjusting the beam splitter T_2. The optical axes should be in only one plane. It is recommended that these adjustments be done in the absence of the test object.

Spherical mirrors may be used instead of the lenses L_1 and L_2. If the diameter is small (less than 150 mm) preference is given to lenses, because an arrangement with spherical mirrors generally results in an unavoidable error or astigmatism. It is sufficient to correct the lenses for spherical aberration.

The arrangement shown in Fig. 1 is preferred for testing models in which edge effects are significant. In this way, the test beam traverses the test region once.

LASER INTERFEROMETER OF THE MICHELSON TYPE

This arrangement of the laser interferometer is characterized by a reference beam whose length is essentially reduced to a practical minimum, as shown in Fig. 2. The beam of the laser La is spread by a short-focal-length objective O. The beam splitter T is placed immediately adjacent to the focal plane of the objective O. The test beam passes from the beam splitter T to the mirror H_2, where it is reflected and returns, thus traversing the test region twice. The center of curvature of the spherical mirror H_2 should coincide with the virtual focus of the objective O. The reference beam also is reflected back on itself by the small spherical mirror H_1, the virtual center of curvature of which should coincide with the center of curvature of H_2. The beam splitter T also recombines the test beam and the reference beam. Finally, an image of the test object M is formed by the objective KO in the image plane BM.

Figure 2 represents a very simple optical arrangement which has proved to be of great utility. It is similar to the knife-edge method of Foucault[24] and to the coin-
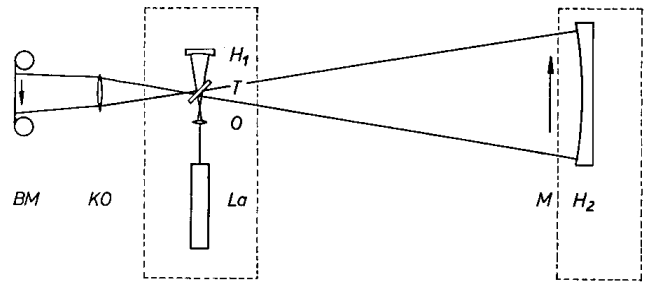

Fig. 2. Light-beam arrangement in a laser interferometer of Michelson type.

cidence method of Toepler[25]. As previously mentioned, the laser La, the objective O, the beam splitter T, and the small spherical mirror H_1 can be housed in a single unit. A second unit consists of the spherical mirror H_2 and its housing. Attention must also be drawn to an antivibration mount. The test object M should be brought as close as possible to the spherical mirror H_2. Because the optical components are housed in two separate units, the test object may be arranged relative to the interferometer in many different ways.

Adjustment of this arrangement is also very simple. After the two units are positioned so that the optical paths are approximately as shown in Fig. 2, the center of curvature of the spherical mirror H_2 is brought adjacent to the beam splitter T by axial displacement of this mirror. The final adjustment is performed by axial displacement of the small spherical mirror H_1 until the concentric interference fringes in the plane BM become straight. The widths of the straight interference fringes can be adjusted by rotating the spherical mirror H_1 or the beam splitter T.

The interferometer arrangement shown in Fig. 2 is well suited for wind-tunnel research, for determination of the optical quality of glass, and for testing spherical mirrors. Because this type is easily adjusted, the interferometer can be brought quickly into operation. Furthermore, the units can be made portable. A very important advantage is the large field of view that can be realized with a spherical mirror. This arrangement is most practical if the test object is short.

For test objects of greater length, an arrangement having a collimated beam is necessary, as shown in Fig. 3. Here, the virtual focal plane of the objective O coincides with the focal plane of the telescopic lens L. The plane mirror PS reflects the collimated beam. The test object is placed into the collimated beam. This arrangement may be easily adapted to a test object of practically any length. There is great flexibility for positioning the test object. The remaining parts of Fig. 2 and the adjustment of the instrument is similar to that previously described.

The arrangement of Fig. 3 is very generally useful and is unsuitable only when edge effects are increased by light passing twice through the test object. This

[24] L. Foucault, Ann. de l'obs. imp. de Paris **5**, 197 (1859).
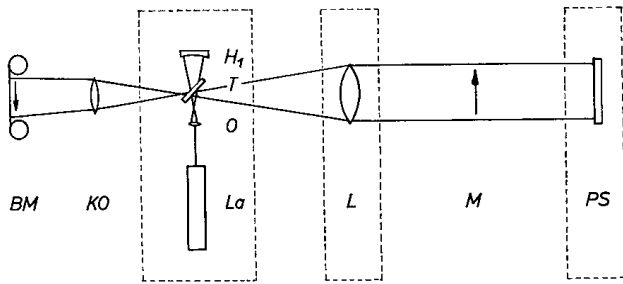[25] H. Schardin, Ergeb. Exakt. Naturw. **20**, 303 (1942).

Fig. 3. Laser interferometer of Michelson type with a
parallel light-beam.

instrument can be used in heat and mass transfer with
liquid or gas phases as well as for special problems in
wind tunnels, for testing surface finish or controlling the
quality of optical components.

When surface finish is tested, the plane mirror PS is
replaced by the test surface. The advantage is a large
effective field of view. It is not necessary to fix the
object surface in order to obtain interference fringes.
Therefore it is possible to test objects at distances of
several meters. The result is an image of the roughness
of the surface as well as of its flatness. This is superior
to the multiple-beam method.[20] It is also possible to
test several planes simultaneously. By this means, two
planes can be made parallel to each other within a
precision of better than 0.3 μ. With a modification of the

Fig. 4.Photograph showing the laser interferometer of Michelson
type with two completely separate units.

instrument shown in Fig. 3, the surface finish and the
geometric accuracy of curved planes can also be deter-
mined quantitatively. If the surfaces have low reflect-
ance, the intensities of the test and reference beams
must be made equal.

The interferometer is well suited for testing objec-
tives, lenses and all kinds of mirrors. The simple opera-
tion is a great advantage compared with the well-known
Michelson and Twyman–Green interferometers. Cavi-
ties, such as air bubbles in glass, become visible in the
form of diffraction fringes.

CONSTRUCTION DETAILS

For most applications, an interferometer of Michelson
type, corresponding to Figs. 2 and 3, may be used. This
type is superior to the Mach–Zehnder interferometer
because its arrangement and operation are simpler.
Furthermore, the instrument is doubly sensitive because
the light beam passes through the test object twice. A
typical interferometer of this type is shown in Fig. 4
which has a light-beam arrangement similar to that
shown in Fig. 2.

The laser used is a Spectra Physics, Inc., He–Ne gas
laser, model 115, with an output greater than 3 mW in
single mode, operating at the wavelength 0.663 μ. With
these conditions, exposure times of about 1/500 sec
were possible when 35-mm film was used. The laser
beam of about 3-mm diameter is spread by a 6✕
microscope objective O (see Fig. 2). The beam splitter
T has an opening 30 mm in diameter. The small spheri-
cal mirror H_1 has a focal length of 45 mm and a diameter
of 10 mm. The large spherical mirror has a focal length
of 1.5 m, corresponding to a 3-m radius of curvature,
and has a diameter of 150 mm. The field of view is
limited by this diameter. The image-forming objective
KO was a simple achromat with 300-mm focal length.
The demands on the quality of the objective are not
high because only a small portion of the lens is used.
From the test object M an image is formed by the
objective KO on the film (Adox KB 14; 14/10 DIN)
in the plane BM.

As indicated by the dotted line in Fig. 2, the inter-
ferometer consists of two units each of which includes
antivibration mounts. Figure 4 is a photograph of the
interferometer shown without its enclosure, which
protects the beams from air currents. The objective KO
and the camera BM are mounted on an arm which is
attached to the pad shown on the unit in the foreground.
The optical axis has a convenient working height of
1.4 m. Each of the two units has a mass of about 350 kg.
Future models will be made lighter and thus more easily
transportable. Both units have a mass of 200 kg hang-
ing from four steel springs, which with damping have a
natural frequency of 1.5 cps. The optical elements are
mounted on this mass. This design has provided a
system completely free from disturbing vibrations.
The instrument in Fig. 4 is at present set up on the
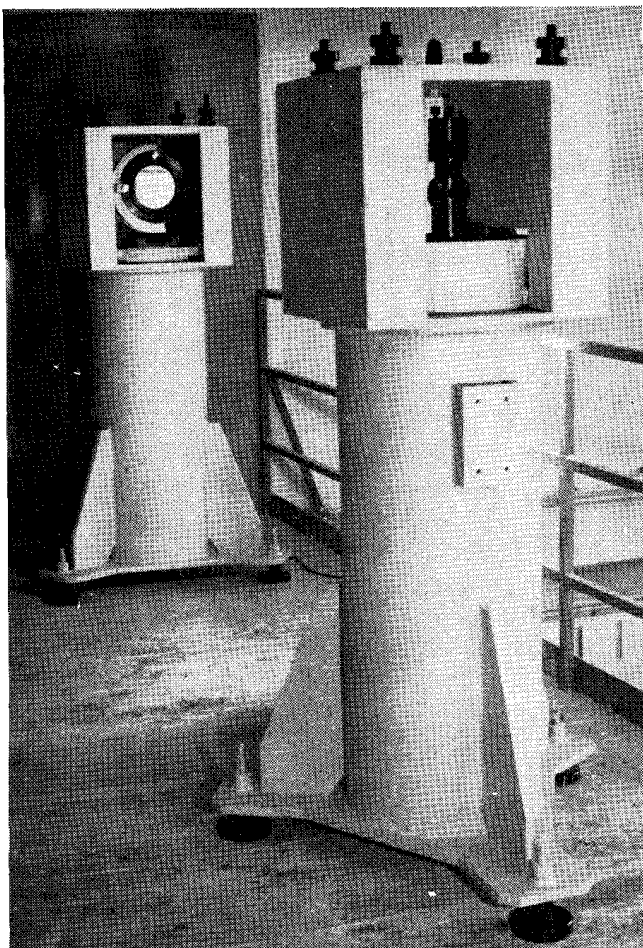concrete floor of a basement laboratory without any

special attempts to isolate from vibration. The labora-
tory building is situated adjacent to a street intersec-
tion having very heavy traffic. The interferometer has
performed uniformly well even under such adverse
conditions. (Examples of interferograms taken under
these circumstances are shown in Figs. 6 to 11). The
large mirror H_2 is installed in the unit shown in the back-
ground of Fig. 4. It is enclosed in a gimbal-mounted
ring. For rough adjustment the mirror and the gimbal
ring can be moved axially in a dove-tail guide.

The other optical elements are located in the unit in
the foreground of Fig. 4. The laser La is installed
vertically. The objective O, the beam splitter T, and
the small spherical mirror H_1 are mounted in an integral
assembly. This assembly can be seen in Fig. 4, in the
middle of the opening; it is shown separately in Fig. 5.
The splitter T can be rotated and tilted for rough
adjustment. The small spherical mirror H_1 is installed
in the head of this unit; it is used to make fine adjust-
ments. The whole head can be shifted in the axial direc-
tion by a threaded ring. The rotation and tilt of the
small mirror H_1 is accomplished by the two knurled-
head screws visible in Fig. 5. These screws have a
backlash-free movement in order to provide continuous
displacement of the mirror H_1 over its full range of
deflection. The mirror is supported by a high-precision
hardened steel ball. After the interferometer has been
set up, these two screws are the only elements of the
interferometer that need to be adjusted. The rough
adjustment of the instrument is simple and can be
done quickly. The adjustment for straight fringes or
zero-fringe field is quite uncritical and can easily be
done by a nonspecialist. Once the adjustment is com-
pleted, the instrument is capable of holding the adjust-
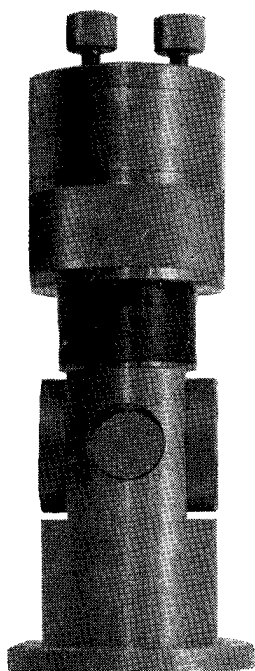ment even under abnormally unfavorable working
conditions.

FIG. 5. Fine-adjustment assembly;
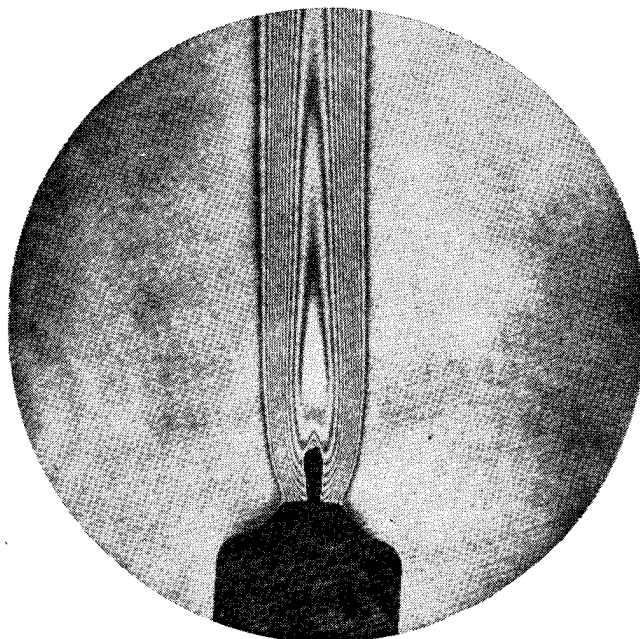reduced to 40% of actual size.

FIG. 6. Temperature field around the flame of a candle.

SOME EXPERIMENTAL RESULTS

In order to demonstrate the capability of the in-
strument, some thermal test objects were photographed.
The field of view has a diameter of 150 mm. Unfortun-
ately, the field of view is not quite clean, as may be
seen in Fig. 6. This results partly from diffraction by
small particles of dust on the optical surfaces and
partly from internal reflections from the surface of the
beam spitter. Although these effects are undesirable,
they do not adversely affect technical utilization of
the photographs. However steps can and are being
taken to eliminate these disturbances by operating the
interferometer in an atmosphere relatively free from
dust and securing a beam splitter which has an effec-
tive antireflection coating.

In Fig. 6 the temperature field around the flame of a
candle is shown. Here the interferometer was adjusted
to produce a zero-fringe field. Because the light passes
through the candle-flame zone twice, the number of the
interference fringes is double that in the well-known
photographs of candles using the Mach–Zehnder inter-
ferometer. This, of course, represents the two-fold
increase in the sensitivity of the present instrument
over the conventional Mach–Zehnder interferometer.

The temperature field around a horizontal heated
cylinder 100 mm in length and 60 mm in diameter with
a temperature 14°C greater than the ambient air is
shown in Fig. 7. In this case, the instrument was
adjusted initially to give straight, horizontal fringes.
Fringes so arranged give more precise results, as is
known.

Figure 8 shows the free convection around a hori-
zontal bundle of tubes in air. Each tube has a length of
100 mm and a diameter of 20 mm. In this case, a
zero-fringe field was established initially. With this
adjustment, the interference fringes are isotherms.

FIG. 7. Temperature field around a horizontal cylinder in air at a temperature 14°C above that of the ambient air.

The temperature difference between any two adjacent fringes is about 3.2°C. Only the bottom tube was heated; it had a temperature about 45°C above that of the ambient air. The other three tubes were heated by the rising warm air.

An interferometer using the arrangement of Fig. 3 was set up for measuring surface finish. In most cases the test objects are relatively small (diameter of the field of view smaller than 50 mm), so that the interferometer was mounted in one single compact unit. It also is important that the instrument be free of vibrations. The test surface is placed in the position of the
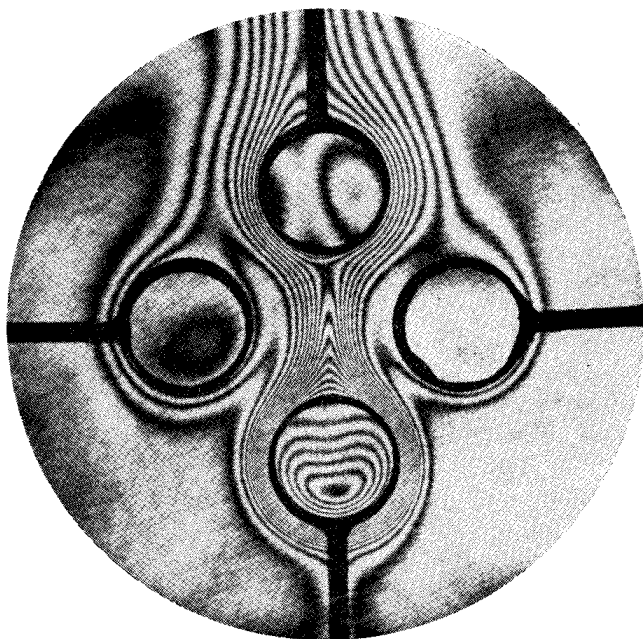

FIG. 8. Temperature field around a bundle of horizontal tubes. Only the tube on the bottom is heated; it has a temperature about 45°C above that of the ambient air.
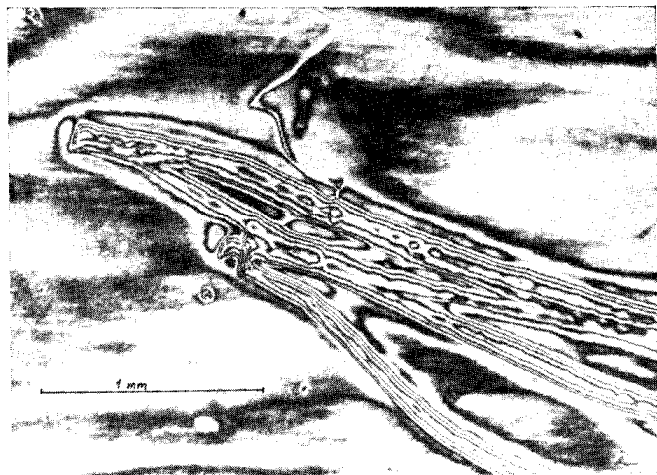

FIG. 9. Scratch (4-μ deep) on a chrome-plated surface.

plane mirror PS, Fig. 3. The objective L had a 125-mm focal distance and about a 30-mm diameter. (Magnified portions of photographs of the interference patterns of the surfaces are shown in Figs. 9 to 11.) The scale is marked in the figures. In these figures, a zero-fringe field was initially established. In this adjustment the interference fringes are lines of equal height (contours). The height difference between two fringes is 0.633 μ.

Figure 9 shows a scratch about 4-μ deep on a chrome-plated surface. The surface itself shows considerable lack of flatness. Figure 10 shows a depression formed by a 10-mm sphere in the same surface. The depression is about 0.2-mm deep. The dark zone results from the large curvature of the depression, which makes it impossible for light from this zone to reach the film. Along the edge of the depression, the plastic deformation of the material can be clearly recognized. In the middle of the depression the concentric interference fringes typical of spherical surfaces can be seen. The deviations from the exact concentricity indicate the quality of the curvature. Figure 10 shows that it is possible to observe interference fringes in two different surfaces simultaneously. This is not possible with conventional surface measuring instruments. Finally, in figure 11 a foil of aluminum fixed on a glass plate was
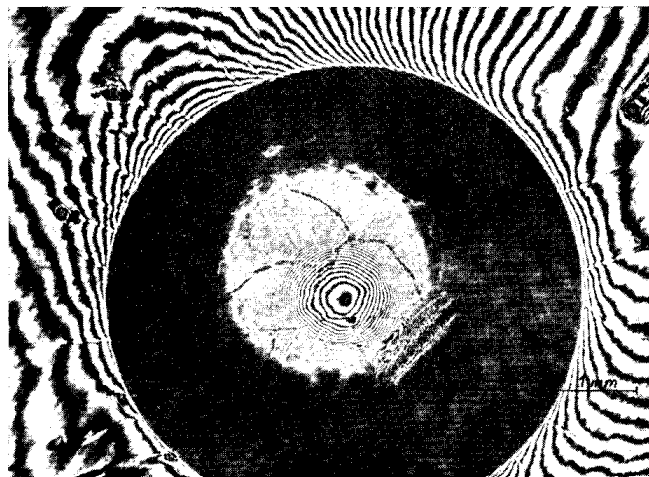

FIG. 10. Depression, about 0.2-mm deep, formed by a 10-mm-diam sphere, in a chrome-plated surface.
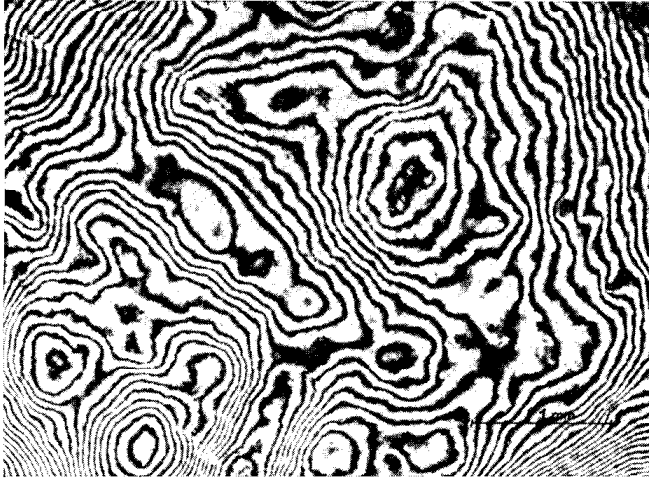
FIG. 11. Interference fringes from an aluminum foil fixed on a glass plate.

tested for flatness and roughness. The surface finish is better than 0.1 μ, but the flatness is quite bad.

SUMMARY

Two-beam interferometry is becoming of increased importance in research and industry. Conventional interferometers require highly skilled and experienced specialists for successful operation. In this paper, a new interferometer is described which is simple to set up, adjust, and operate. This instrument retains the desirable properties of conventional interferometers. It makes use of the unusual coherence properties of laser light.[26] Two main types are described. In one the test beam passes through the test object only once, as in Mach–Zehnder interferometer; in the second type, the test beam passes through the test object twice, as in the Michelson interferometer. In this type the test object can be a reflecting surface. Applications of this instrument range from research to quality control of surfaces. A prototype of the new interferometer is described, consisting of two separated units designed to be free of vibrations. The instrument is portable and experience has shown it to operate well under adverse conditions. Operation of the instrument is simple, requiring little skill or experience. Typical results from thermal systems and surface-finish measurement are given.

ACKNOWLEDGMENT

[26] After the authors had finished this paper they learned of the publication R. J. Goldstein, Rev. Sci. Instr. 36, 1408 (1965), in which Goldstein describes a laser interferometer of a different type.