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Holography and its applications

Dennis Gabor and George W. Stroke

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The discovery by one of the authors in 1948 of a new branch of interferometry—holography—held promise as a means for the lensless photography of three-dimensional objects, but further progress was retarded by the lack of a sufficiently coherent source of light. This deficiency was remedied in spectacular fashion by the invention some thirteen years later of the laser and led to the important advances described in the present paper. After outlining the basic mathematical theory of holography the authors discuss a number of its currently successful applications which include pattern recognition, stress analysis, colour photography, and three-dimensional microscopy.

Holography is a method of photography by coherent light in which a light wave issuing from an object is 'frozen' into a photographic emulsion by means of a second beam of coherent light, and afterwards 'revived' by the second beam alone. A brief explanation of the meaning of optical coherence will be given later.

First called 'wavefront reconstruction', holography was initiated by one of us in 1948, in an attempt to increase the resolving power of electron microscopes. It was well known that these instruments could never attain the potentially enormous resolving power of de Broglie waves, because electron objectives could not be made perfect. The intention was to obtain better micrographs in two stages. In the first stage a 'hologram' was taken by the interference of the electron waves diffracted and scattered by the object with a 'coherent background'; the illuminating electron wave itself. The term hologram means a complete picture, (from the Greek '*holos*', 'the whole') because it contains information on both amplitudes and phases. This complete but scrambled picture, had then to be unscrambled and 'reconstructed' in an optical system, which was a scaled-up and corrected simulation of the electron-optical system. The feasibility of this process was first demonstrated, in 1948, in an optical 'model experiment'.

In the 15 years that followed its discovery, holography found few applications because of the weakness of coherent light sources, but had a spectacular revival in 1961, when the laser, a matchlessly powerful source of coherent light, became available. The impact of the laser on the field of coherent optics was enormous, and its possibilities are still far from exhausted. The first laser-holograms, already much superior to those of 1948, were obtained by E. N. Leith and J. Upatnieks in 1962, and soon after by many other workers. The most remarkable early achievement of holography was the lensless photography of three-dimensional objects, to be followed by the photography of three-dimensional objects in natural colours, by holographic (non-simultaneous) interferometry, pattern recognition, de-blurring of pictures, and many other technical achievements. Holography is now a flourishing laboratory industry. Most of its industrial applications are yet to come but their outlines are already visible, for example, in non-destructive testing, three-dimensional portraits, holographic microscopy, 3-D cinema projection, new communication and information storage techniques, and the extension of the holographic principle to other wave phenomena, in order to achieve vision by ultrasonic and electromagnetic waves.

Holographic imaging — the basic mathematical theory

Let us take a photographic plate in a plane x, y, and illuminate it simultaneously with a reference beam A and an object beam B. These two waves must be coherent, that is, they must be capable of interfering with one another, which means that when they are superposed they must be capable of producing local darkness. This is possible only if they consist of long, regular, nearly sinusoidal wave-trains, in other words, the light must be highly monochromatic. Then, and only then is it possible to produce darkness by superposing the crests of one wave with the troughs of the other. The length of the regular wave-trains determines the coherence length, that is to say the distance by which one wave-train can be offset relative to the other, and still be capable of interference. When holography began, the best, relatively powerful coherent light source was the high-pressure mercury lamp, with a coherence length of about 0·1 mm. The helium-neon laser, when it came on the market in 1962, had a coherence length of about 30 cm. Since that time it has been improved, at somewhat reduced power, to 10 m, and recently there were reports of lasers with coherence length of 1000 m. It is the coherence length that limits the geometry of holographic arrangements. So long as the path differences of the two beams A and B remain within the coherence length, one can consider them as regular oscillations, and deal with them by the same formalism as used for alternating currents in electrical engineering, as the following simple theory shows.

Let $A(x, y)$ and $B(x, y)$ be the complex amplitudes of the two beams in the plane x, y of the photographic

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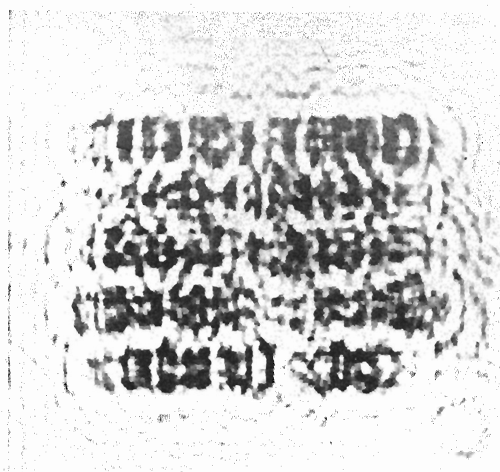
s born in Hungary in 1900 and educated at the Technical Universities of dapest and Berlin; he worked in the British electrical industry from 1934 948. He became Mullard Reader in Electronics at the Imperial College of ence and Technology, London, in 1949, and was appointed to the chair Applied Electron Physics on its creation in 1958. He is now Professor meritus of the University of London and a Senior Research Fellow at Imperial College. He is also Staff Scientist at CBS Laboratories, Stamford, Connecticut and Visiting Professor at the State University of New York at Stony Brook. His work has been in electrical and electronic engineering, and in applied physics, with particular interests in the development of high-speed oscillography, gas discharges, colour television, and physical optics.

George W. Stroke, *Dr. ès Sc., F.A.P.S.*

Was born in Yugoslavia in 1924 and studied physics at the University of Paris. After spending some ten years in research on the diffraction grating ruling and velocity of light measurements at the Massachusetts Institute of Technology from 1952 to 1963 and four years as a Professor of Electrical Engineering at the University of Michigen, he became in 1967 Professor of Electrical Sciences and Medical Biophysics and Head of the *Electro-Optical Sciences Center* at the State University of New York at Stony Brook. His main interests are in coherent optics, interferometry, diffraction gratings, and holography and its application to biophysics.



Hologram

Original

Reconstruction

Figure 1 The first holographic reconstruction by D. Gabor, 1948

plate. To be more precise, the value of one component of the electric vector at x, y at time t is

$$[A(x,y)+B(x,y)]e^{-i\omega t}$$

This is really a somewhat too precise description, because the temporal factor $\exp(-i\omega t)$ is strictly unobservable in optical experiments. It has a physical meaning, however, in sound and microwave holography. In optics it soon drops out, because the photographic plate or any other physical detector ignores the phase, and records only the absolute resulting intensity

$$I=|A+B|^2=(A+B)\ (A^*+B^*) \qquad \ldots.(1)$$

where the asterisk denotes the complex conjugates. In detail

$$I=(AA^*+BB^*)+(AB^*+A^*B) \qquad \ldots.(2)$$

The first term is the sum of the individual intensities, the rest is the interference phenomenon, that is to say the fringes. The total energy contained in the fringe structure is zero. Note that in optics we always obtain only the whole second bracket: in sound or microwave holography we could pick out the AB^* or the A^*B terms singly, which can be a considerable advantage.

Let us now process the exposed plate, and illuminate it with the reference beam A alone. To simplify the explanation we assume for the moment that the processing is such that it gives an amplitude transmission t proportional to I. The intensity transmission is then proportional to I^2, that is to say the processing is done with a gamma[1] of -2. We now obtain immediately behind the hologram a transmitted amplitude

$$A.t=\underset{\text{illuminating wave}}{A(AA^*+BB^*)}+\underset{\text{twin wave}}{A^2B^*}+\underset{\text{reconstructed wave}}{AA^*B} \qquad \ldots.(3)$$

The first term represents essentially the illuminating wave, because the factor (AA^*+BB^*) is almost always nearly uniform. (Except if one puts the object right against the hologram plate.) It is the last term which is of great interest, because if A is a plane wave, AA^* is a constant, hence the last term is essentially B, the object wave, as if the object were in position and radiating just as it was in the recording. But, by Huygens' Principle, if the wave is right in one plane, it is right everywhere, apart from the diffraction arising by the limitation of the plane, which is usually negligible. Hence we have completely reconstructed the original object wave B. We obtain however, in addition, a 'twin wave', A^2B. If the reference wave A is incident at right angles to the plate, $A=const.$ and A^2 and AA^* will differ only in an unimportant and unobservable phase factor. In this case the twin wave is B^*, which corresponds to a mirror image of the object B, relative to the hologram plane. (If A is a spherical wave, it will, very nearly, be a mirror image relative to the wavefront A, considered as a spherical mirror.) But if A is a skew wave, so that $A=\exp(iKx)$, we have $AA^*=1$, but $A^2=\exp(2iKx)$. This means that the true image B is recorded on a uniform background, but the conjugate image B^* on a grating, with wave number $2K$, and this will produce a difference in the direction of emission.

Figure 1 shows one of the first holographic reconstructions obtained by D. Gabor in 1948. Owing to the weakness of the coherent source the experiment had to be carried out on a very small scale, with an object of only 1·5 mm diameter. The reconstruction is somewhat marred by dust particle and specks in the cementing of the lens, because in coherent light every little particle leaves a long wake, but chiefly by the presence of the conjugate image, which intrudes between the lines. This was effectively eliminated only in 1962 by Leith and Upatnieks, by using a skew reference wave, made possible by the superior coherence length of the laser. A year later these authors and one of us (G.W.S.), effected a further important improvement by diffuse illumination of the object (figure 2). This had two consequences. It largely eliminated the long coherent wake of dust particles and the like, which are so disturbing in regular illumination, but more important, it made it possible to view three-dimensional reconstructions with two eyes. Holography was of course, three-dimensional from the start, but one could see the depth of the reconstructed object only by focusing on it with a short-focus eyepiece, because the hologram extended only as far as the beam

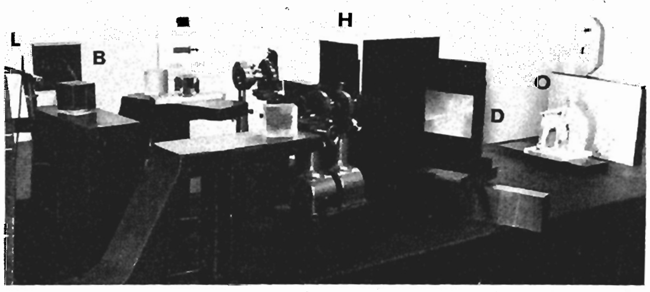
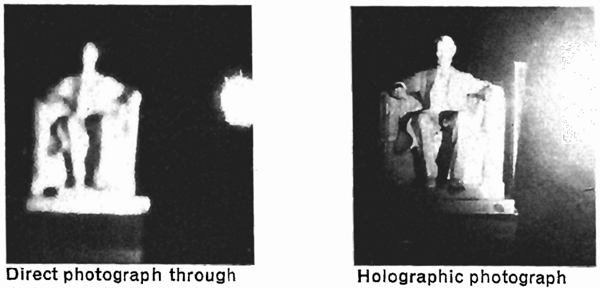


Figure 2 Arrangement used for the recording of a hologram in diffused light. L, laser (helium-neon 6328Å); B, beam-splitting prism; O, three-dimensional object; D, diffusing glass; H, hologram plate; M, reference mirror.

[1] Gamma is the rate of change of photographic density with log (response) and is a measure of the contrast obtained in a given film emulsion after a given processing.

Figure 3 Three-dimensional virtual image as seen by looking through a bleached (transparent) phase hologram when it is illuminated by the laser in the back of it.



Direct photograph through distorting glass

Holographic photograph recorded through distorting glass

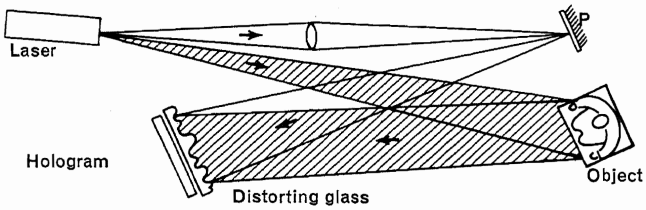


Figure 4 Imaging through distorting (turbulent) media. Compensation of imaging through distorting media by use of lensless Fourier-transform holography recording arrangement. (After G. W. Stroke, C. Puech, and G. Indebetouw (1968).)

diffracted by the object. By illuminating the object in a wide angle, for instance with a large frosted glass, it now became possible to extend the hologram of any small part of the object over the whole plate, so that it could be seen with the unaided eye, from any direction. The hologram thereby became less and less like the object, in fact it assumed a completely random appearance, but the reconstruction became completely lifelike, as is strikingly shown in figure 3.

Figure 4 (lower diagram) illustrates holography in more physical-geometrical terms. It shows the interference pattern of two (approximately) plane waves, which gives a system of parallel fringes, and the interference of a plane wave with a spherical wave which gives the concentric 'Fresnel zone' pattern. One can always consider a hologram as constructed of these basic building blocks. If there are many of them, the pattern looks meaningless to the eye, but it can be at once unscrambled by illuminating it with the original reference wave.

Our basic equation (3) expresses all this, and a lot more. In all probability it has not yet been completely exhausted. We will now discuss briefly a few of its consequences.

First, it is not necessary to observe the rule 'gamma $= -2$'. For other values of gamma, instead of equ. (3), a binomial expansion is obtained, but so long as the background A is strong, the leading term in B will be linear, and of the same form as in equ. (3). Though a beam ratio of unity is the optimum, the brightness of the reconstructed image relative to that of the reference beam falls off only slowly with the beam ratio. It is not necessary to have a negative gamma in the processing of the hologram, or to take a print of it; on the contrary, printed holograms are never quite as good as the original. There is hardly any difference between positive and negative holograms, except of course if the object is very close to the plate.

Secondly, the hologram need not be illuminated with the same plane or spherical wavefront as used in the recording. A shifting of the illuminating point will produce only an optical transformation of the reconstructed object. One can also illuminate with another wavelength. Moreover, the coherence requirements in the reconstruction can be much reduced for visual observation. It is not necessary to have coherence over the whole hologram, only over the small area which a cone from a reconstructed object point to the eye pupil cuts out in the hologram plane. One can therefore in most cases reconstruct holograms with monochromatic mercury or sodium light, and with advantage, as this reduces the very annoying 'laser speckle' caused by excessive coherence.

Thirdly, there is no need for the hologram to be plane, it can be any surface. In our derivation of equ. (3) we assumed a plane hologram for simplicity, but we have not made explicit use of its planeness. Moreover, there is no need for it to be a surface without depth. We would have obtained the same results had we operated with scatterers, dispersed in a volume instead of distributed in two dimensions. There is hardly any difference between thick emulsions and thin ones so long as the interference fringes in the various layers substantially obscure one another for the illuminating light. But when this is no longer the case, when the light penetrates through several fringe-systems, curious new phenomena arise, namely: colour selectivity and directional sensitivity, to which we will return later.

Fourthly, there is no need for the reference wave, the 'key' wave which fixes and revives the object beam, to be plane or spherical. The reciprocal relation between two waves A and B which is achieved by their product terms in equ. 2 is, within very wide limits such that A can revive B and B can revive A. There are two conditions for this. One is evident; the 'key' wave must extend over the whole hologram. The other condition, less evident, may be stated without proof: the Fourier transform of the key wave must correlate sharply with itself. A plane wave satisfies this condition ideally, because the Fourier transform of a plane wave is a point, and this of course correlates absolutely sharply with itself. But it can be also very well satisfied by waves issuing from complicated objects, full of detail, especially when positive and negative phases alternate in them. If one superimposes two copies of such an object, a sharp maximum of light transmission will be obtained only if they exactly cover one another. This is true for many complicated patterns such as fingerprints and Chinese ideograms. To some extent also ordinary Roman letters can be used as key objects to emit key waves which will then translate one pattern into any other.

This is the basis for pattern recognition, character recognition, and general coding by holography. It is possible to detect a given shape, for instance, a vehicle, in an aerial photograph, by first taking a hologram of the vehicle with a wavefront which converges to a point in a certain plane. If we then illuminate the hologram with the aerial photograph containing the vehicle, a sharp point will appear at the position of the vehicle. The weakness of the method is only that though the vehicle in the photograph can be at any place, it must be oriented parallel to the position in which the hologram was taken, and it must be of the original size. By the same principle it is also possible to translate, for instance, Chinese ideograms into the corresponding English sentences, or letters or words into codewords for computers.

There is still a fifth most interesting property embodied in equ. (3) which is the basis of holographic interferometry.

Let us take two photographs, in succession on the same plate of two objects B and C, with the same reference wave A. This will give, taking only the essential part of equ. (3), a transmission (or absorption, or scattering) component

$$A(B+C) \qquad \ldots.(4)$$

and in the reconstruction

$$(AA^*)(B+C) \qquad \ldots.(5)$$

that is, the two waves which have been frozen into the emulsion at different times will be revived simultaneously in the reconstruction, and they will interfere with one another, though they have never 'seen' each other before!

This 'non-simultaneous interferometry' is now probably the most flourishing engineering application of holography. One can superimpose for instance two holograms of a beam, one stress-free, the other deformed, and observe the Newton-fringe pattern corresponding to the deformation. One can also take one hologram only, process it, put it back, and observe the deformation fringes 'live.'

Deep (volume) holograms

Shortly before lasers had led to the revival of holography in 1962, the Soviet physicist, Yu. N. Denisyuk, had the felicitous idea of combining holography with the old method of photography in natural colours invented by Gabriel Lippmann in 1891. He showed theoretically, and also in some practical experiments using a reference beam passing through the emulsion in the recording, that if the reference beam and the object beam fall on the emulsion from opposite sides, there will be reconstruction of the object by reflection from the emulsion (by 'Bragg diffraction', like the reflection of X-rays by crystals) and not by transmission, as with the holograms previously discussed. The idea of volume holograms was also proposed independently at the same time, by P. J. van Heerden, with the object of three-dimensional optical storage, Denisyuk could not quite translate his ideas into practice, as he had no laser. This was achieved only in 1965 by G. W. Stroke and A. Labeyrie, who were also the first to show that such holograms could be made to reconstruct images with ordinary incoherent white light, and thus to produce multi-colour three-dimensional images from ordinary (albeit very fine-grain) black-and-white emulsions, notably when the reference beam was made to be incident on the back of the emulsion during the recording.

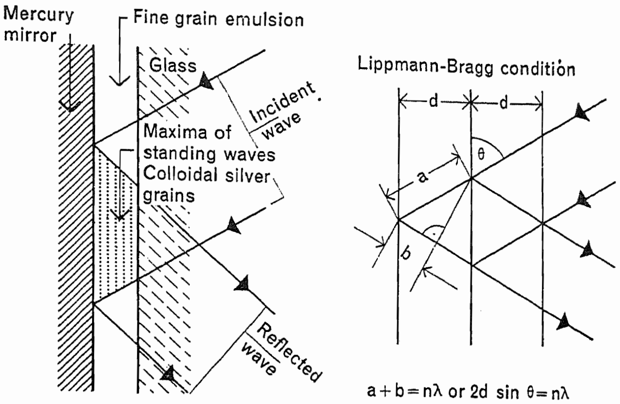


Figure 5 Lippmann colour photography, 1891.

To make his colour photographs, Lippmann had first to produce 'Lippmann emulsions', that is, emulsions with colloidal silver bromide, having grain sizes of 100–700 Å only. He then turned his plate glass-side towards the lens, and backed the emulsion with a mercury mirror (figure 5). The incoming light waves then formed standing waves with the reflected waves, and fine silver grains were precipitated in the antinodes, that is to say in the maxima of the electric vector. When such a plate is illuminated with white light, only those wavelengths are reflected whose wavelets, scattered at the silver grain layers, add up in phase, and this is the original light. It is remarkable that one emulsion can store not just one wavelength, but a whole spectrum. Up to 16 well-separated colours can be stored in modern Lippmann emulsions, such as EK 649F and AGFA 8E 75. The reason is that so long as the scattering power is so small that multiple scattering can be neglected, the process is linear, each spectral line producing its own stack of Lippmann layers.

Denisyuk combined this principle with the basic idea of holography, by taking a Lippmann emulsion and illuminating it with the object beam and the reference beam from opposite sides (figure 6). The Lippmann layers are now not parallel to the emulsion plane, but bisect the direction between the object ray and the reference ray. When such a plate is then illuminated with the reference beam alone, the illuminating ray will be reflected at the Lippmann layers in the direction of the original object ray; this is as if the object were in position and, moreover, in the original colour.

Figures 9 and 10 show early examples of colour holography. Figure 9 is a precursor of the reflection method; it is a transmission hologram taken with two laser wavelengths (red and blue), and reconstructed in the same

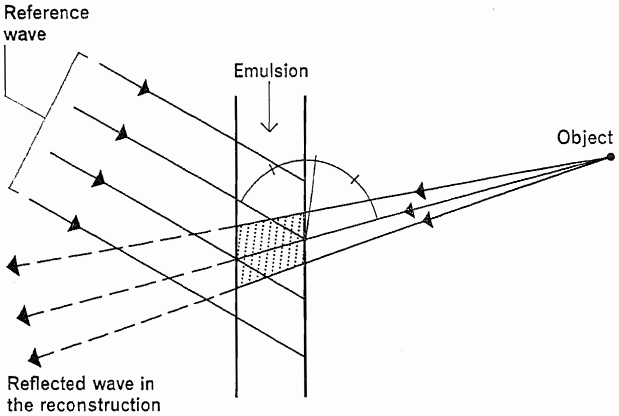


Figure 6 Combination of holography and Lippmann colour photography. Proposed by Denisyuk (1962), van Heerden (1963), and first realized by Stroke and Labeyrie in 1965.

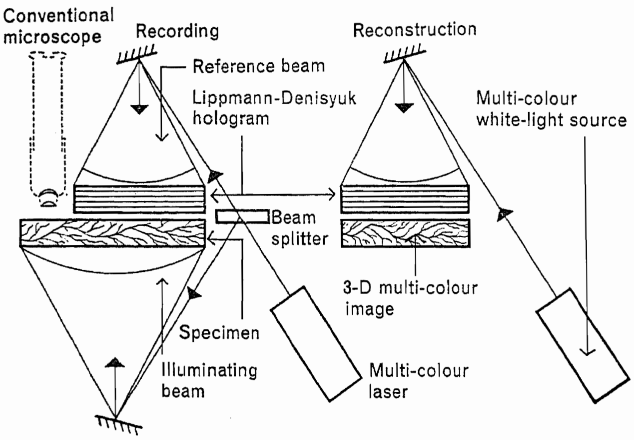


Figure 7 A white-light reflection hologram recording arrangement as applied in high-resolution wide-field three-dimensional microscopy. (Stroke and Labeyrie).

light. Though it is a transmission hologram, it makes use of the Lippmann effect, because the reference beam made a large angle with the plate normal. Figure 10 is the first reflection hologram taken by Stroke and Labeyrie, that could be reconstructed in white light. Figure 11 is a more recent example of a white-light reflection hologram.

Besides colour selectivity, a new phenomenon arises in deep holography, namely, directional selectivity. A plane hologram can be illuminated from almost any direction; the reconstructed image turns with the reference beam. But a deep hologram can be illuminated only within a few degrees out of the original direction before the image vanishes. This phenomenon is of great mportance in two applications. The first is condensed formation storage, (as originally proposed by van eerden) because many data can be stored in the same lume of the emulsion or of a light-responsive crystal, nd can be evoked at will by illumination in sharply defined directions. The other potential application is three-dimensional projection, for instance of cinema pictures, without the need for glasses. Here it is essential that the image projected by one projector shall be visible only to eyes in certain zones of the cinema, for instance to left eyes, and the image from the other projector only from another set of zones, at the right of the first, for right eyes. This is a problem which is quite insoluble by orthodox optical means, but can be solved if the projection screen is made into a large, deep hologram, which images one projector on one set of the viewing zones, and the other projector on the other set. Much technological work will have to be done before this bold project can be realised, but the possibility exists, for the first time.

Figure 7 shows a very satisfactory solution of the problem of multi-colour high-resolution 3-D microscopy with a wide lateral field. A fine-grain photographic plate is placed very close to the object, and a Lippmann-Denisyuk hologram is produced on it, by illuminating it from both sides as shown. This permits the recording of the high-angle diffracted beams, as required for high-resolution, simultaneously across the widely-extended lateral field. We see here an illustration of the remarkable capability of holograms for storing vastly more high-resolution pictorial information simultaneously over a very great depth and very extended lateral field, than is attainable with any other form of image-forming device. Figure 8 is an example of such an extended micro-hologram. In the reproduction it is of course impossible to give an idea of its very considerable depth.

Holographic interferometry

Holography has made it possible to produce 'one-armed' interferometers, in which the waves that are brought to interference pass through the same optical track—but not simultaneously. This is now one of the most active engineering applications of holography. Three types of holographic interferometry can be distinguished:

(1) Double exposure, of an object in two positions consecutively, one displaced or distorted relative to the other.

(2) Taking a hologram of the object, processing it, putting it back into place and then observing the displacement or distortion of it 'live', through the hologram.

(3) Holographic interferometry of vibrating objects, that is, exposing the plate through one or several vibration cycles.

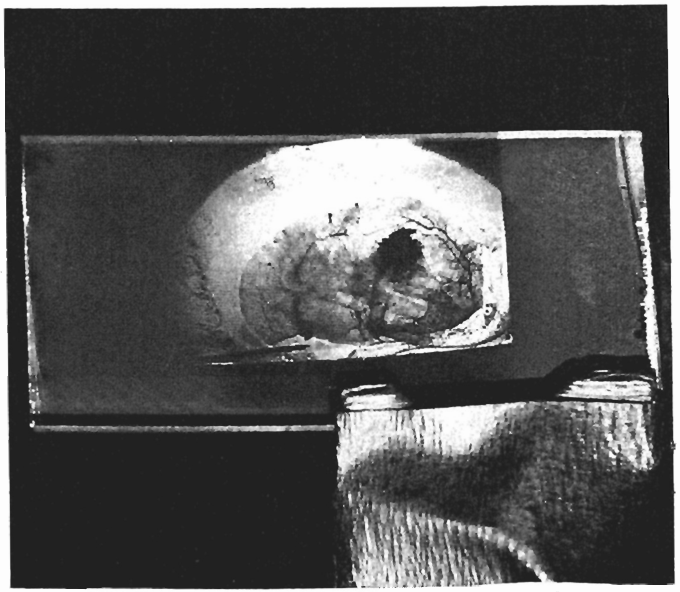


Figure 8 Holographic microscopy. Image of a 30 mm wide section of a guinea-pig's ear (3 mm thick whole mount) reconstructed in white-light from a white-light reflection hologram and showing normal blood vessels (the black spot is formed by injection of some India ink into the lymphatic system). (After G. W. Stroke and J. F. Burke.)

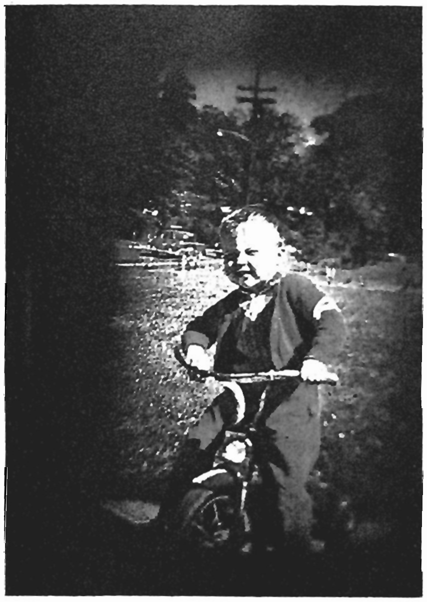


Figure 9

Figure 10

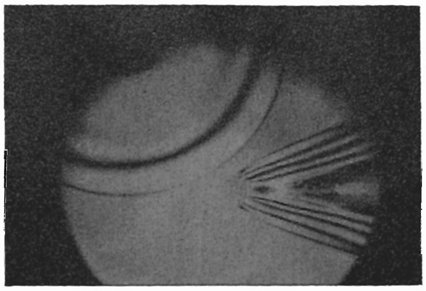


Figure 12 (a)

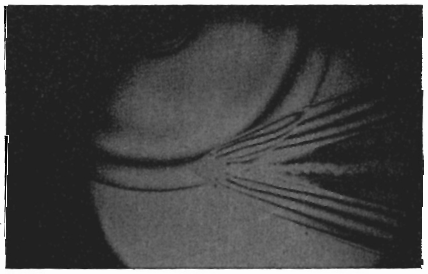


Figure 12 (b)

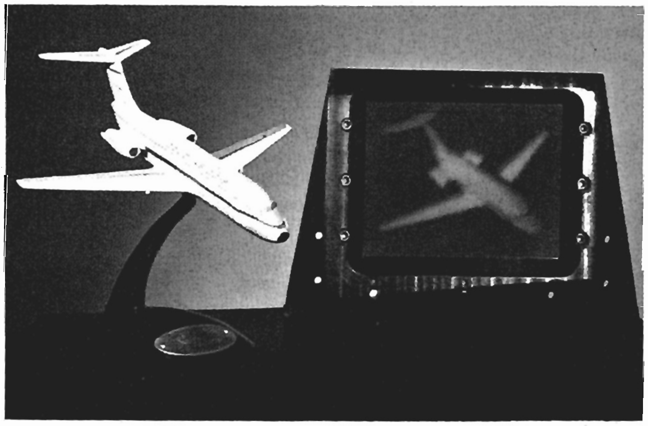


Figure 11 White-light multi-colour reflection holography. Three-dimensional image reconstructed from Lippmann-Bragg volume reflection hologram using method of Stroke and Labeyrie (*Phys. Lett.* **20**, 368, 1966). The hologram is shown on the right and the object on the left. (By courtesy of R. G. Zech, Conductron Corp., Ann Arbor, Michigan.)

Figure 9 First multi-colour image to be reconstructed with laser-light (not white light) illumination from a transmission hologram, recorded in the light of two laser wavelengths (6328Å helium-neon, and 4880Å argon-neon) by K. S. Pennington and L. H. Lin. (*Appl. Phys. Lett.* **7**, 56, 1965). (Reproduced by courtesy of R. J. Collier, Bell Telephone Laboratories, Murray Hill, New Jersey.)

Figure 10 First example of a multi-colour image reconstructed from a hologram of the Stroke-Labeyrie Lippmann-Denisyuk reflection type using ordinary white light. (After Lin, Pennington, Stroke and Labeyrie, *Bell Sys. Tech. J.* **45**, 659, 1966.)

Figure 12 Two successive, carefully timed double exposed holographic interferograms recorded with a Q-switched pulsed ruby laser, showing the interaction of two shock waves. One of the waves is the shock-wave envelope surrounding the 22-250 bullet flying at 1160 m/s and the spherical wave is produced by an electric spark discharge. Exposure time 100 ns. (By courtesy of R. E. Brooks, L. O. Heflinger, and R. F. Wuerker, TRW Systems, Redondo Beach, California.)

The first method offers unique possibilities, in particular when used with pulsed lasers, and has been exploited with spectacular results (figures 12a, b). The pulsed ruby laser enables a picture of a flying bullet to be taken in 30 ns, during which it moves by less than 0·025 mm. Moreover, by taking first (or subsequently) a hologram of the clear field, without the bullet or shock waves, one obtains not just a picture, but a three-dimensional hologram which can afterwards be explored in depth, at leisure.

The almost unlimited focal depth of holograms has been also strikingly demonstrated in the form of a hologram taken of 20 cm of pond-water. By raking the microscope through the reconstruction, the microfauna could be focused throughout this depth!

This development led also to the first commercially available holographic research instrument; the 'Disdrometer', an apparatus for taking holograms of aerosols, jets from nozzles, and the like. It is now possible to take a hologram of the jet as it leaves the nozzle of a jet engine with supersonic velocity, from a distance at which the heat does not damage the photographic plate, and afterwards to examine the droplets, which may have diameters of a few microns, with a microscope only.

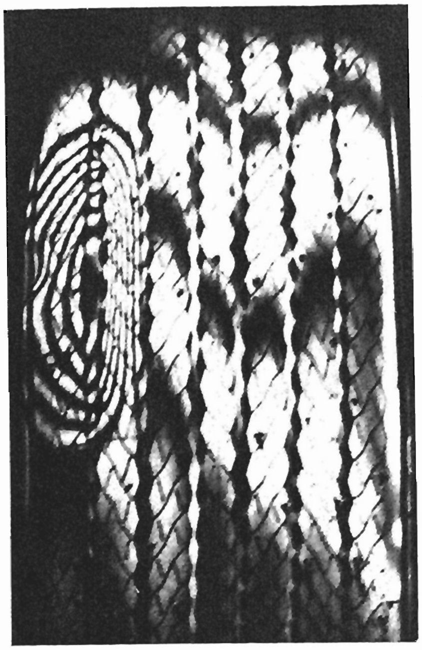
Figure 13 is an example of 'live' interferometry, showing the application of holographic interferometry to the testing of whole motor-car tyres, with an accuracy of fractions of a micron, when microscopic defects, hidden at depths of the order of centimetres, are revealed.

Figure 14 is a most interesting example of double-exposure holographic interferometry. The transparent box which contained the turbine blades was filled once with air, and once with SF_6, two gases with refractive indices sufficiently differing, (by about 1%) to produce beats between the wavelengths in the two cases of 0·58 mm, or about 100 light-wavelengths. The profile of the turbine blades can then be checked to an accuracy of about 0·025 mm.

Figure 15 is an example of the holographic interferometry of vibrating objects, in this case a loudspeaker.

Holographic image de-blurring

Holography began with an attempt to sharpen electron



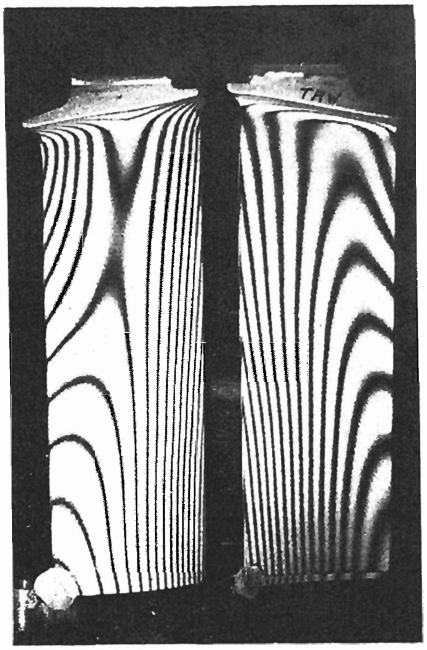


Figure 13 (left) Real-time holographic interferogram of a full-size motor-car tyre, obtained by replacing the hologram of the tyre (recorded in continuous-wave 6328Å helium-neon laser light) into its recording position and observing the tyre through its own hologram. The interference fringe system reveals a defect (deformation resulting from an inside separation of the outer ply and the thread). (By courtesy of Dr. R. M. Grant, GC-Optronics, Ann Arbor, Michigan.)

Figure 14 (right) Holographic contour mapping of turbine blades using method of T. Tsuruta and N. Shiotake. (*Japan J. Appl. Phys.*, **36**, 232, 1967.) (By courtesy of Dr. R. F. Wuerker, TRW Systems, Redondo Beach, California.)

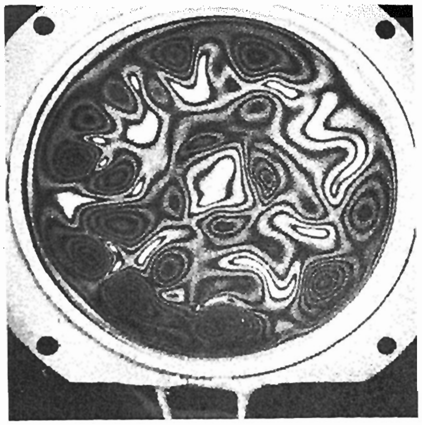
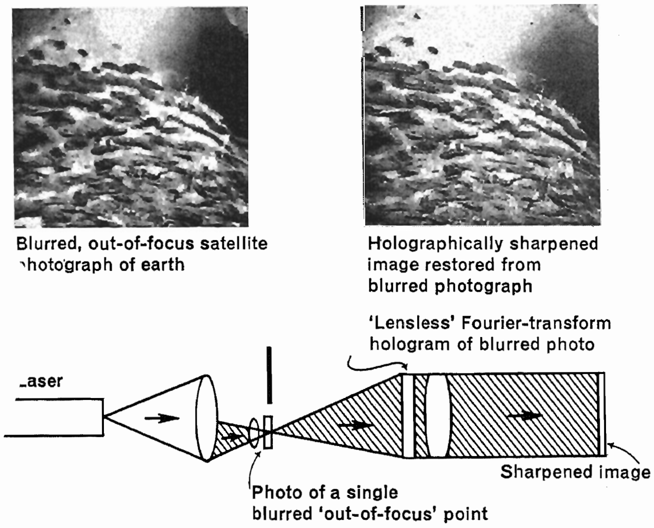


Figure 15 Time-averaged interferometric hologram of a 6-inch loudspeaker vibrating at 2 kHz. The interferogram was recorded in continuous-wave helium-neon laser light (6328Å) by making the reference field interfere with the multiplicity of holograms corresponding to the different instantaneous positions of the vibrating membrane, all suitably superposed successively in the same hologram emulsion. The white central regions, and those appearing on the side correspond to non-vibrating regions. The first dark fringe around the white regions indicates the locus of the points on the loudspeaker vibrating with an amplitude of about 0·2 λ, and so on. (By courtesy of Dr. R. M. Grant, GC-Optronics, Ann Arbor, Michigan.)



Blurred, out-of-focus satellite photograph of earth

Holographically sharpened image restored from blurred photograph

Figure 16 Holographic image-sharpness restoration using the method of extended-source lensless-Fourier-transform holography compensation (G. W. Stroke, *Phys. Letters*, **27A**, 405, 1968).

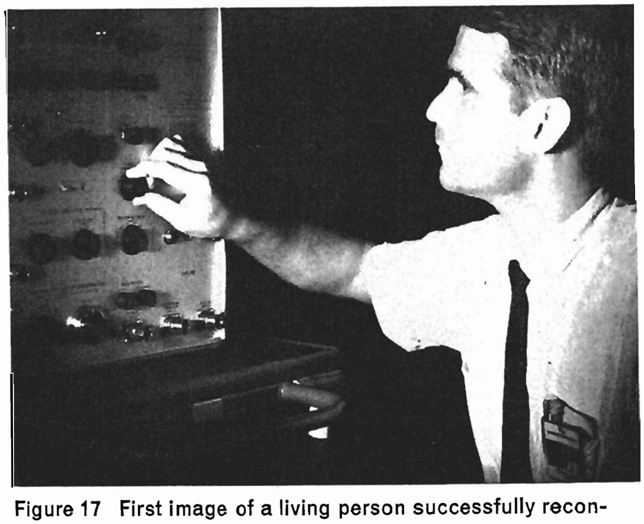


Figure 17 First image of a living person successfully reconstructed from a pulsed laser hologram. The hologram was recorded with the aid of a high-coherence pulsed ruby laser system (L. D. Siebert, *Appl. Phys. Lett.*, **11**, 326, 1967). (By courtesy of D. Ansley and L. Siebert, Conductron Corp., Ann Arbor, Michigan.)

micrographs blurred by the spherical aberration of electron objectives. In the meantime the sharpening of optical images has attracted considerable interest. The first successes were scored by A. Maréchal and P. Croce, in 1953, by a method of optical Fourier-filtering, which was notably improved by J. Tsujiuchi, in Maréchal's institute in Paris. A similar method, using computers, for the sharpening of radio-astronomical images was translated into practice by several radio-astronomers, in particular, J. P. Wild. G. W. Stroke has recently developed a particularly simple and effective method of sharpening defocused or otherwise blurred photographs in which a lensless 'Fourier hologram' of the blurred photograph is produced. In this method the reference beam issues from a point source in the same plane as the object. This imitates, without any lens, a Fourier transformation to a very good approximation, because the interference fringes between any spherical wave issuing from a point of the object and the spherical reference beam of the same radius will be straight and parallel.

Figure 16 shows the restoration of an accidentally blurred out-of-focus NASA photograph of the Earth, taken from the U.S. Satellite GEMINI XII. The original was a 55 × 55 mm colour photograph.

This holographic method of deblurring is much simpler than previous 'deconvolution' methods, and immensely superior to computer methods of deblurring.

Other applications and future possibilities of holography

A practical application of holography just within our reach is holographic portraiture. The difficulty is of course that living persons cannot be expected to keep still within a quarter of a wavelength ($< 10^{-4}$ mm) during a prolonged exposure. Only pulsed lasers can overcome this difficulty, with exposure times of 100 ns or less. A very promising start has been made recently, as is illustrated by figure 17 which shows the first holographic portrait. This was taken with a pulsed ruby laser, which was not only powerful, but had the exceptional coherence length (for ruby lasers) of at least 1 m.

Work on 'seeing' by microwaves is considerably more advanced. In fact, revival of holography was preceded by brilliant work on the optical reconstruction of coherent radar data by L. J. Cutrona, E. N. Leith, C. J. Porcello, and others before 1960. The efforts of the radio astronomers, in particular of J. P. Wild with his recently inaugurated Culgoora Radioheliograph, are also important steps in this direction.

An application that shows considerable promise is the use of holograms as generalized optical elements. A lens can transform a point into another point. But a hologram can transform a point, (the focus of the reference beam) into a three-dimensional statue of Abraham Lincoln. One has only to present a photographic plate with two coherently illuminated objects simultaneously, when it will behave as an optical system that transforms one object into the other. An example of such an application which has yet to be realized on a practical scale is the three-dimensional projection screen. Other possible applications are 'redirectors' (J. M. Burch's term) which transform the complicated multimode pattern of a laser into one mode, and made-to-measure diffusers.