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Holography

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DK 535.411

Der herkömmliche photographische Prozess besteht in der Aufzeichnung einer beleuchteten dreidimensionalen Szene in der Form eines zweidimensionalen Bildes auf einer lichtempfindlichen Platte. Das von der Szene bzw. vom Objekt reflektierte Licht wird auf die lichtempfindliche Platte mit Hilfe einer Linse fokussiert.

Die Holographie ist ebenfalls ein photographischer Prozess, sie unterscheidet sich aber beträchtlich von der Photographie, denn hierbei wird nicht ein Abbild des Objekts, sondern die vom Objekt reflektierten Lichtwellen selbst aufgezeichnet. Das Ergebnis, das völlig anders aussieht, als das Objekt, wird Hologramm genannt. Zur Herstellung eines Hologramms wird meistens das kohärente, monochromatische Licht eines Lasergerätes verwendet. Dieses Licht wird in zwei Strahlen aufgeteilt; einer davon wird auf das Objekt gerichtet, von wo aus er auf eine lichtempfindliche Platte reflektiert wird; der zweite Strahl trifft direkt die Platte. Wenn die somit belichtete photographische Platte entwickelt und mit dem gleichen Licht, wie für deren Herstellung verwendet wurde, beleuchtet wird, so entsteht ein echt dreidimensionales Bild des Objekts (Bilder 2b und 2c zeigen zwei photographische Aufnahmen der räumlichen Rekonstruktion eines Hologramms; dabei verblüfft, wie sich die Abstandsfokussierung der Kamera auswirkt).

Mit Hilfe einer Doppelbelichtung können zwei Wellenfronten zugleich aufgezeichnet werden, so dass die Interferenz zwischen den beiden Belichtungen gemessen bzw. verglichen werden kann. Bewegt sich das Objekt zwischen beiden Belichtungen, so entstehen Interferenzlinien in der Form von Hell-Dunkel-Zonen. Dieser Effekt erlaubt genaue Verformungsmessungen an einem Objekt, wenn es sich beispielsweise bei der ersten Belichtung in Ruhe befindet und bei der zweiten unter Spannung gesetzt wird. Auf diese Weise sind sogar Verformungen in der Grössenordnung von 0,1 µm erkennbar.

Im ersten Teil dieser Arbeit, die wir in der Originalfassung in englischer Sprache veröffentlichen, werden die Grundlagen der Holographie erläutert und die Hauptschwierigkeiten, besonders bei Messungen in Produktionsstätten, gezeigt.

Im zweiten Teil, der in der nächsten Ausgabe erscheint, untersucht der Verfasser die Leistungsfähigkeit eines typischen holographischen Systems. Mit Hilfe einfacher mathematischer Zusammenhänge zeigt er die Grenzen des Systems in bezug auf: 1. Grösse des zu holographierenden Objekts, 2. Entfernung zwischen Aufnahmegerät und Objekt, 3. die zu erwartende Genauigkeit, Empfindlichkeit und Auflösevermögen bei der Spannungsmessung. M. K.

The Principles

The conventional photographic process consists of recording an illuminated three-dimensional scene as a two-dimensional image on a light-sensitive surface. The light reflected from objects is focused on the sensitive surface by some kind of image-forming device such as a lens.

Holography is a quite different method of photography, in which instead of recording an image of the scene one records the reflected light waves themselves. The result, which looks quite different from the original scene, is called a hologram. Using it one can produce a three-dimensional reconstruction of an object or scene upon which measurements can be made at leisure.

When light falls on a point the scattered light travels outwards from it as a series of expanding shells. These are analogous to the circular waves produced when a stone is dropped into a pond. A complicated object behaves like a collection of points, and the composite scattered wavefront is the result of superimposing the effect of each. The essence of holography consists of recording both the amplitude and the phase of this complicated wavefront over some arbitrary surface in space. Ordinary photography can be used to record the amplitude by converting it to corresponding variations in the opacity of the photographic emulsion. The emulsion is not, however, sensitive to the relative phases of waves falling on it, and in order to record these one has to use interferometry.

Fig. 1a shows a simple case of interference: two plane waves impinging at different angles on a photographic plate. At some parts of the plate the waves will be permanently in phase; at these places the amplitudes will add to produce a greater light intensity than would have been produced by either wave on its own. At other places the waves will be in antiphase, and these places will be permanently dark. The net result is a set of alternately bright and dark fringes which form a sort of grating structure. The intensity of illumination in fact varies sinusoidally across the plate. If the exposure and subsequent processing is arranged so that the transmission of the plate becomes proportional to the intensity, the result is a sinusoidal diffraction grating.

When the diffraction grating is illuminated by a collimated beam of monochromatic light several plane waves are generated by the interaction of the light with the grating structure as shown in Fig. 1b. These plane waves are radiated in directions determined by the periodicity of the grating. One can account for the diffracted waves by regarding each infinitesimally narrow grating element as a line source radiating cylindrically shaped wave fronts which reinforce one another in certain directions. At a distance from the grating, large compared with its periodicity, the net result is three plane waves. One travels in the same direction as the illuminating wave, while the two others, the first-order waves, are propagated at equal angles on either side.

If the direction of the illuminating wave is the same as that of one of the original waves, one of the first orders will travel in the same direction as the other original wave and can be considered to be a "reconstruction" of it. The sinusoidal grating is in fact a hologram of a plane wave.

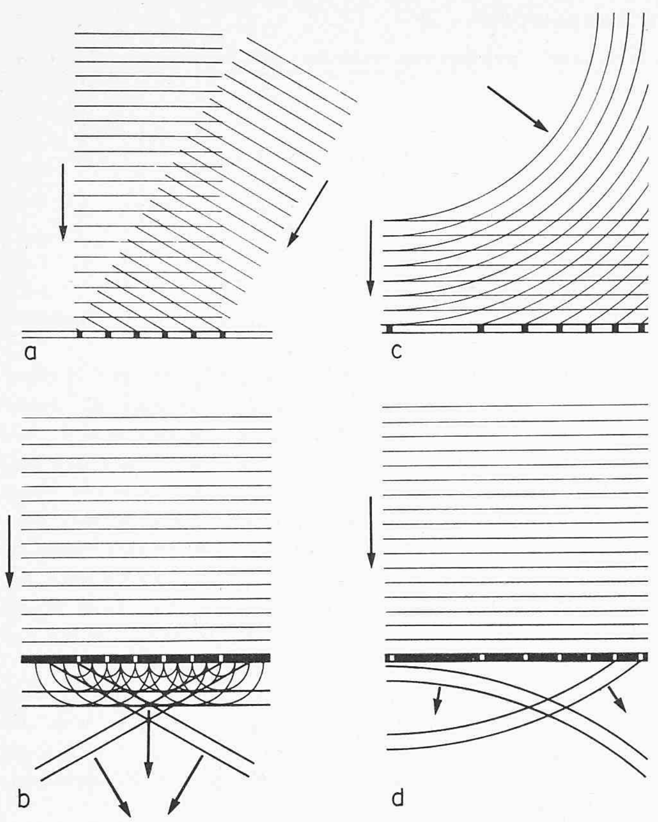

Figure 1. Some simple holograms
- a Making a hologram of a plane wave
- b Reconstructing from a hologram of a plane wave
- c Making a hologram of a cylindrical wave
- d Reconstructing from a hologram of a cylindrical wave

Interference of a cylindrical wave, produced by a line source, with a plane wave is shown in Fig. 1c. Again fringes are produced, but this time they are unequally spaced. If the plate is processed and illuminated by a plane wave three waves are emitted, a zero-order and two first-order waves. This time, however, the two first-order waves are curved as shown in Fig. 1d. One appears to come from the position of the original line source, while the other converges on a line on the other side of the plate and hence produces a real image of the original line source. Two reconstructions are produced, one at the same relative position as the source and the other at a conjugate position on the other side of the plate. They are known as the virtual and real reconstruction, respectively.

Extending this it is easy to see that the hologram of a point source is a series of unequally spaced concentric circles. Again there will be a real reconstruction and a virtual reconstruction, as well as the zero-order or background wave. The hologram of a point source is better known as a zone plate. A complicated object can be regarded as a collection of point scatterers, each of which produces a component on the hologram plate.

In general, when a hologram is made, two beams of light are caused to fall together on a photographic plate. When the plate is developed and illuminated with one of the beams the other beam is emitted. Usually the first beam is a simple one which can easily be produced again, such as a plane wave, while the other is a complicated wavefront scattered from some object or scene. The two beams are often known as the "reference wave" and the "object wave" respectively. When the reconstructed wavefront falls on the eye its lens focuses and one sees the original object in truly three-dimensional form Fig. 2b and 2c. By changing one's view point one can see different aspects of the object just as one could if it were really there.

Practical Requirements

The first requirement is that the reference wave and the object wave must be in a fit state to interfere with one another. This means that the two waves must be coherent. To illustrate the coherence requirement we consider a given point on the photographic plate. While the hologram is being made this point receives light from both the object and the reference beam. Clearly, in order to record anything the phase difference between the light from the object beam and that from the reference beam should not change appreciably over the period of exposure. Furthermore, the object wave is itself made up of components which must also remain constant over the period of the exposure. This illustrates the two coherence requirements. Both waves must be spatially coherent and the two waves must not shift phase relative to one another during the period of the exposure. In practice this means that a laser is necessary to make worthwhile holograms.

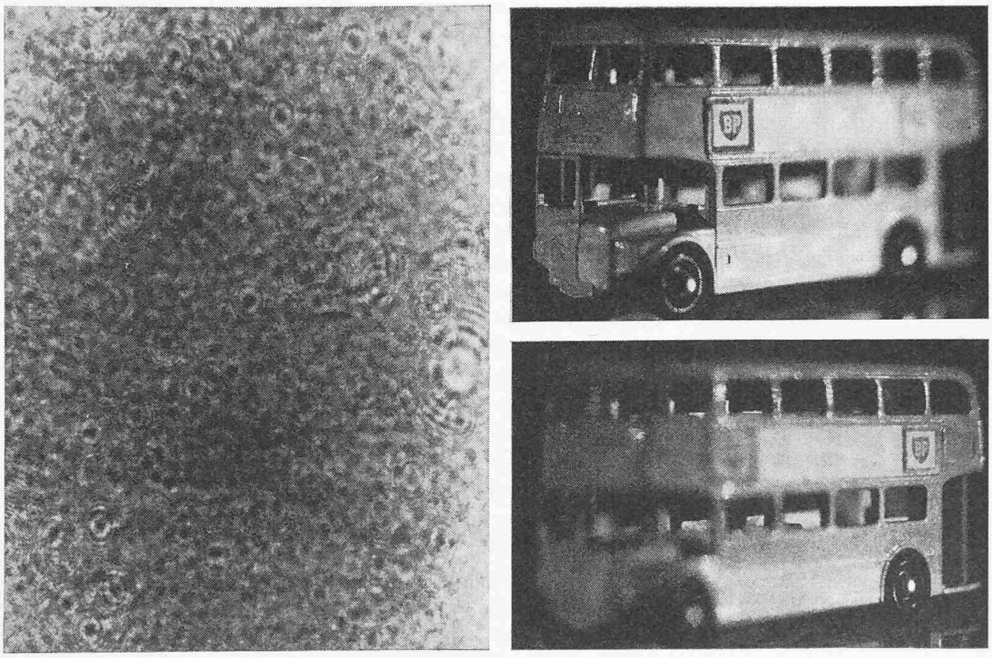

Figure 2.
- a (left) contact print from a hologram
- b (above, right) photograph of the reconstruction from the hologram
- c (below, right) another photograph of the same reconstruction

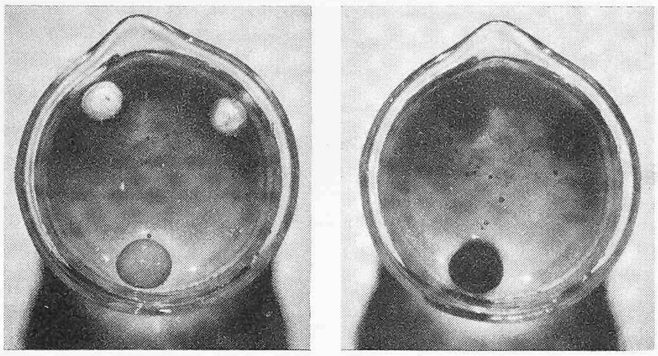

Figure 3. Effect of movement on holographic reconstructions

a (left) reconstruction of beads which had moved less than a small fraction of a wavelength during the holographic exposure

b (right) reconstruction of beads in motion

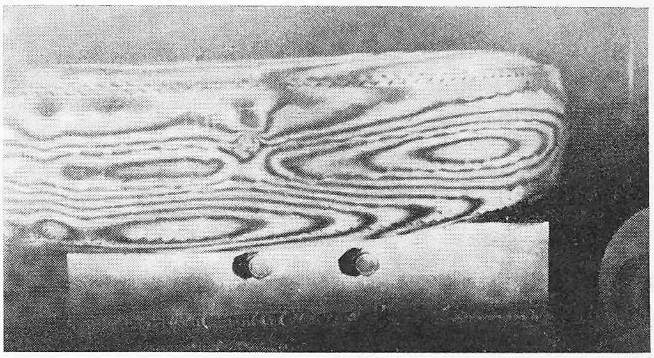

Figure 4. Double exposure hologram of a car tyre

In general, except in certain specialized applications, everything must be kept very still during the recording process. For example, consider what would happen if the photographic plate were moved while recording the sinusoidal diffraction grating. If the plate moved upwards at a constant speed, so that it moved one fringe spacing in the time of the exposure, the result would be uniform blackening of the photographic plate and of course no reconstruction would be possible (Fig. 3a and 3b). If the distance from an object to the photographic plate is changed by one wavelength during an exposure, the fringe system moves transversely through one fringe spacing and uniform blackening is the result. Clearly some components are more critical than others, and systematic movements so that a component ends up in a different place at the end of an exposure are more important than random ones. Random movements reduce the visibility of the fringes and hence result in poorer reconstructions. Repetitive vibrations with a period short compared with the exposure time are acceptable, and in fact holograms of such objects can be made to reveal modes of vibration.

It is usually convenient for the object beam and the reference beam to be inclined at quite large angles relative to one another. This results in very closely pitched interference fringes. It goes without saying that the photographic plate must be capable of resolving the fringes, and in practice this means that very high resolution plates must be used. If for example the angle between the beams is 90°, plates which will resolve rather more than 2000 line pairs per millimetre are required.

Holography in an Engineering Environment

The difficulties

The most usual way of making holograms is to employ a continous-wave laser with an output of between 1 and 100 mW. The laser light is split into two beams (eg, by means of partially silvered mirror), and one of the beams is then directed at the object, and thence scattered towards a photographic plate, while the other is allowed to fall directly on the plate. When the plate is developed and illuminated by a replica of the reference beam, the light scattered by the object is reconstructed, so producing an image of the object in truly three-dimensional form.

Using double exposures it is possible to reconstruct two wavefronts simultaneously, and hence to make interferometric comparison between them. For example, if an object moves between exposures, the relative movement is visible as a fringe pattern when the hologram is reconstructed, and consequently, if an object is strained between exposures, defects are revealed as anomalous patterns. These patterns are usually easy to identify, and enable the location of the defect to be determined. Displacement anomalies of as little as 0,1 μm can be detected, and once a fault has been located, it can, if required, be further investigated by more conventional techniques. The holographic technique is of course non-contacting and is applicable to all normal surfaces (see, for instance Fig. 4).

Since it requires no detailed fringe interpretation, flaw detection is obviously a particularly attractive application of holography, but it does pose some practical problems in an actual engineering environment. One of the main problems arises from the high level of vibration usually found in engineering workshops. There are, after all, very stringent limits on the amount of movement which can be tolerated during a holographic exposure, since any change in the optical path from the laser to the hologram plate reduces the intensity of the holographic reconstruction. If, for example, we assume that optical paths change at a constant rate, Fig. 5 shows that a change of one eighth of a wave length corresponds to a reduction in intensity of about 5%. It is more difficult to put a tolerance on movement *between* exposures, since the effect depends partly in the geometrical arrangement but much more on the type of movement. Rotation about an axis in the surface

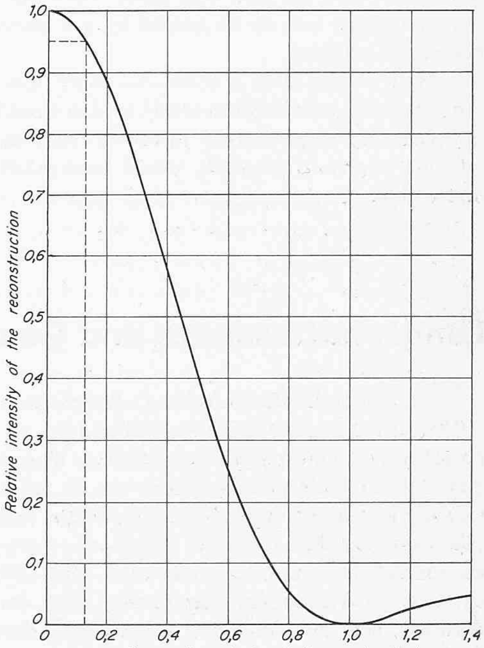

Figure 5. Effect of change in optical path during a holographic exposure (a linear change is assumed)

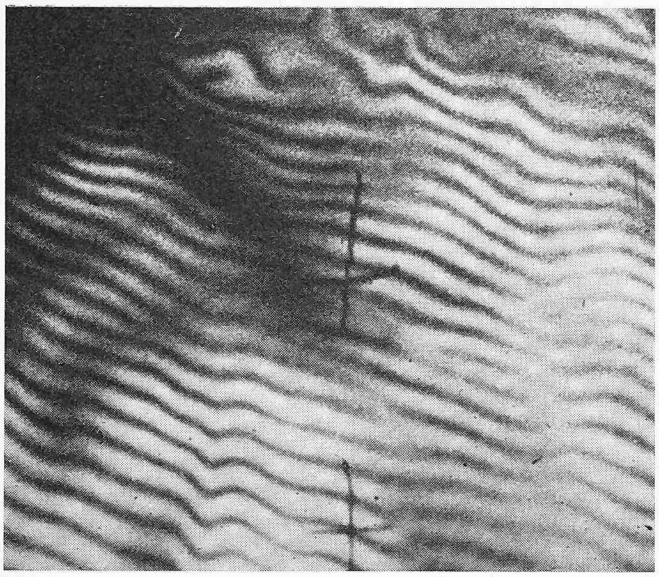

Figure 6. Double exposure hologram of a pressure vessel during hydraulic pressure testing

is most troublesome, and must typically be kept below about 7×10^{-4} radians, but simple translational movement is more acceptable and its main effect is to make photography of the final results more difficult.

Thermal air currents are also a hindrance to practical holography, producing variations in optical path from exposure to exposure and so distorting fringe patterns and making flaw detection difficult.

Holography in a shipyard workshop

The Applied Physics Division at the Atomic Weapons Research Establishment (AWRE) was confronted with all these problems when allotted the task of making double-exposure holograms of part of a large pressure vessel in a shipyard heavy-engineering workshop. The holograms had to be made in the course of a hydraulic pressure test, during which normal heavy-engineering activities would be going on in the neighbourhood; and the task was made more difficult by the fact that the vessel was to be heated by gas burners immediately before the exercise.

Had we had only a continous-wave laser at our diposal, the high ambient vibration levels, which would have produced unacceptably large changes in optical path during the several seconds' exposure required, would have rendered holography impossible. Fortunately, we had recently dicsovered that quite simple modifications to one of our ruby lasers made it sufficiently coherent for holography. The modified laser was capable of delivering about 50 mJ of energy in about 30 ns (it was Q-switched using a passive dye), and with such a short exposure time, mechanical stability no longer posed a problem and there was no difficulty in making a single-exposure hologram. However, the laser had to be allowed to cool down for 3 min after each exposure, and the presence of thermal air currents between exposures could still therefore represent a source of interference. One minor practical problem – how to exclude ambient light from the hologram-making apparatus – was finally solved by using a light-proof tent connected to the pressure vessel by a shaped hardboard tunnel.

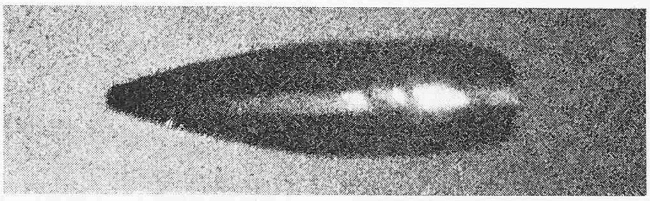

Figure 7. Reconstruction from a hologram of a bullet travelling at 3000 ft/s (914 m/s)

Fig. 6, which is a photograph of the reconstruction from a double-exposure hologram, illustrates the results obtained. The pressure change between exposures was 100 lb/in^{2}. The scale may be deduced from the two crosses marked on the vessel wall, the distance between them being 7,5 cm. The basic, approximately horizontal fringe pattern is due to a vertical movement of the vessel, together with a small amount of bowing outwards relative to a stiff region in the lower part of the field. The coarse shadowy structure can be ascribed to slight errors in the alignment of an aperture in the laser cavity, the main effect being to reduce the illumination of parts of the vessel.

Clearly, considerable advantages accrue from using even a very modest pulsed laser such as ours. The stability requirement can be greatly relaxed, and holograms can therfore be made cheaply, quickly and without disrupting other activities in the vicinity. Obviously room exists for some improvement in the pulsed laser. There is, however, no very pressing need to reduce pulse length since objects travelling at a speed as high as 3000 ft/s have been holographed with the existing pulse length (see Fig. 7). Pulse repeatability has likewise been shown to be good enough to avoid spurious fringes in most practical situations. Energy could, however, be usefully increased to enable larger objects to be accomodated. Notwithstanding it can be validly claimed that pulsed holography is already a practical non-destructive testing technique.

Fortsetzung im nächsten Heft

Landschaftsschutz und Gemeindeautonomie

DK 711.28

Sinnvoller Landschaftsschutz bezieht sich in den meisten Fällen auf ein grossräumiges Gebiet, das in seiner topographischen und landschaftlichen Struktur eine Einheit bildet. In den meisten Fällen überschreiten die zu schützenden Gebiete Gemeinde- und oft auch Kantonsgrenzen. Landschaftsschutzpläne müssen darum in der Regel von einer übergeordneten kantonalen Instanz erlassen werden. Dass dabei Spannungen entstehen zwischen der kantonalen und der gemeindlichen Planung, liegt auf der Hand – Probleme, deren Lösung vom Verhältnis der kantonalen Kompetenz zur Planung und der kommunalen Planungsbefugnis im Rahmen der Gemeindeautonomie abhängt. Mit diesen Zusammenhängen befasste sich das Bundesgericht eingehend im Fall *Cully* (BGE 98 Ia S. 427 ff.) gegen den Staatsrat des Kantons Waadt. Nach dem waadtländischen Baugesetz vom 5. Februar 1971 können die Gemeinden Pläne aufstellen und Bau- und Planungsreglemente erlassen. Diese Befugnis ist durch die Kompetenz des Kantons beschränkt und bedingt, seinerseits kantonale «Siedlungspläne» und entsprechende Bestimmungen aufzustellen, die im Konfliktfall den kommunalen Plänen und Bestimmungen vorgehen. Zudem steht dem Kanton eine Zweckmässigkeitskontrolle der kommunalen Pläne und Baureglemente zu.

Das Bundesgericht misst im vorliegenden Fall dem Umstand eine wichtige Bedeutung zu, dass der Plan der Gemein-