Omnidirectional holography

Pal Greguss

Department of Manufacturing Engineering
Budapest University of Technology and Economics
Budapest, Hungary H-1111
e-mail: greguss@manuf.bme.hu

Abstract

Omnidirectional holograms (ODH) are based on Centric Minded Imaging (CMI), and are characterized by a single-shot recording technique. ODHs, when reconstructed, display a space that can be "walked around," and render a 360° panoramic view. They can be used for display holography, nevertheless, their main future is in panoramic metrology, especially, interferometry.

Introduction

Holography in general means the creation of a 2D light-intensity distribution on a 2D surface from a 3D environment in such a way that, if the recorded intensity pattern is properly illuminated, a scene can be seen which creates a similar 3D space impression as the original 3D environment created in our *mind*. We observe the seen geometric relations, including distance differences, parallax, etc., however, we cannot grasp the object's scene, they are in a 3D - however, *virtual* - space, with other words, in our *cortical* space.

It is well known that the technique which allows to create a 2D intensity pattern with the properties described above was introduced by Dennis Gabor (1948) and was named "holography", to emphasize that this method allows simultaneous recording of amplitude bound and phase bound information (holos = all, graphein = recording) on a square-law detector, such as a photographic plate or film.

However, strictly speaking, a classical, conventional hologram - in spite of the fact that it is a pictorial representation of space and time data, - never records all the data carried optically from the 3D environment, only from a restricted chunk of space. The reason for this lies in the fact that Gabor started also from the generally accepted philosophy of vision, namely, that the intrinsic geometric structure of our 3D space, and consequently, that of our *visual space*, is spherical, and that our visual system uses for imaging the so-called see-through-window (STW) strategy. (Fig. 1)

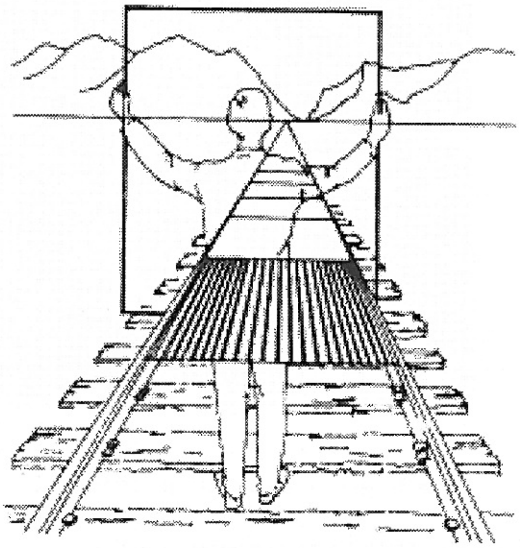


Fig 1. See-through-window (STW) imaging strategy

Therefore, to obtain a pictorial representation of all optically carried data from the 3D space, i.e., a 360° panoramic view, one has to turn himself around the vertical axis and "put together" in time the data obtained from the instantaneously perceived view, the sense of sight - the gaze.

That such space chunks can be "put together" holographically was first shown by

King (1968), from which idea the so-called "multiplex hologram" or "stereo-hologram" was developed. In this case, the "adding" of the space chunks is performed holographically, using a cylindrically shaped film holder. The drawback of this "adding technique", although it renders a wonderful 3D impression (Fig. 2), is that the panoramic image perceived in the visual field becomes somewhat "falsified", since the visual fields of the "added" space chunks are not recorded simultaneously, there is a time lapse between each recording. To overcome this problem and to create a valid and real omnidirectional hologram, one has to abandon thinking in STW imaging, and switch to CMI.

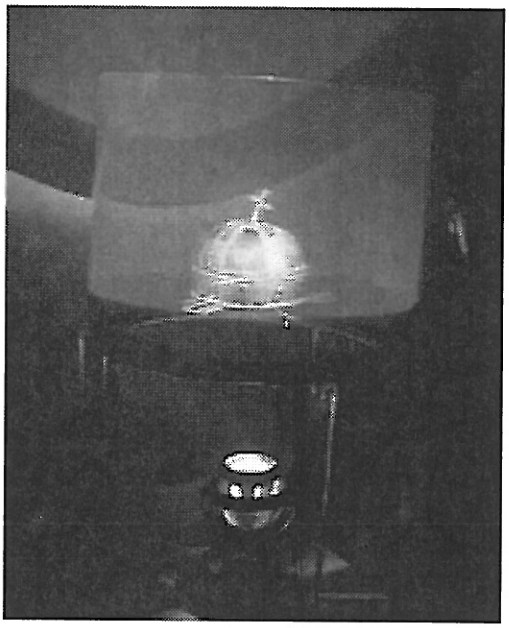


Fig. 2. Multiplexed hologram of the Hungarian St.Stephen's Crown (of the original)

Centric Minded Imaging (CMI)

In contrary to STW imaging, CMI assumes the visual space to be cylindrical, rather than spherical. This consideration is backed up by the observation that Mother Nature operates with a similar philosophy, since, e.g., stereopsis exists only horizontally, further, vertical parallax is less important for us than horizontal one.

According to CMI, the radius of the cylinder of vision is equal to the vision distance. The panoramic view of the image volume shows up on the wall of this imaginary cylinder, and is transformed to a plane perpendicular to the axis of the cylinder. (Fig. 3)

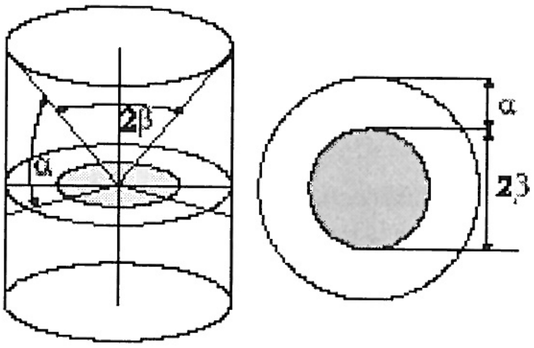


Fig. 3. Philosopy of CMI

The main difference between STW imaging and CMI is that to create an image, i.e., *2D light intensity distribution* on a 2D surface, Cartesian coordinates are used in the first case, and polar coordinates in the second one. As a consequence, STW imaging is dealing with multiple vanishing points, while CMI has only a single one. Thus, the 3D environment shows up as a two-dimensional skeleton and renders an omnidirectional view of the 3D scene in the virtual space. This imaging technique is also referred to as Flat Cylinder Perspective (FCP).

Although in everyday life we are in general not faced with problems calling for CMI strategy, our mind is capable of creating a 2D skeleton of the 3D environment. However, to display it on a two-dimensional surface, to form again and again the space chunks and then perceive it in the cortical space, some techniqcal assistance is needed.

It is interesting to mention that already Shakespeare knew about such a type of approach of artists of his epoch, since he writes in Richard II:

> *"For sorrow's eye, glazed with blinding tears,*
> *Divides one thing entire to many objects;*
> *Like perspectives, which, rightly glazed upon,*
> *Show nothing but confusion, eyed awry,*
> *Distinguished form."*

Since the 2D skeleton of the 3D space is being formed again and again, the technique is called *anamorphic*, the word coming from the Greek "*ana*" = again, and "*morph*" = form. Several methods exist to display anamorphic images, some of them are using, e.g., conical mirrors, some others cylindrical mirrors. When looking at these mirrors, an image is seen in reflection, appearing undistorted inside the vertically placed mirror, and when turning the image, a 360° panoramic view can be experienced.

First attempts

Endeavors to record single-shot ODHs, i.e. holograms which, when reconstructed, display a space that can be "walked around", started practically immediately after the rebirth of holography, i.e., after the creation of the first lasers.

According to the suggestion of Hioki and Suzuki (1965), a cylindrical film holder was to be used, and the object was illuminated through the non-silver part of a thin convex spherical mirror placed in the axis of the cylinder. (Fig. 4)

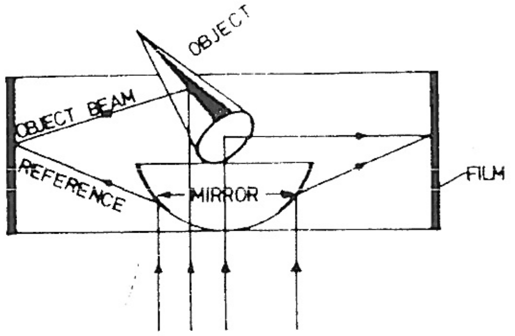


Fig. 4. ODH approach of Hioki and Suzuki

The light reflected from the silver portion of the spherical mirror served as a reference background. After developing the film and placing it in the cylindrical holder, the object showing up in the virtual space, when illuminated with a parallel laser beam, could be walked around. However, the reconstructed image was rather poor, full with severe distortions. Jeong et al. (1966), using photographic plates in the form of a cube, instead of a cylindrical film, improved the quality of the reconstruction. However, limitation of both approaches issued from the fact that the illumination during recording was not really uniform because the laser light was plane polarized, and the reflectance of the mirror depended upon the relative orientation and/or shape of the mirror.

A real progress in ODH came when Jeong (1967) eliminated the reference mirror, and used a laser beam expanded by a high-power microscope objective that illuminated the cylindrically shaped photographic film with the emulsion facing inside the cylinder. (Fig. 5)

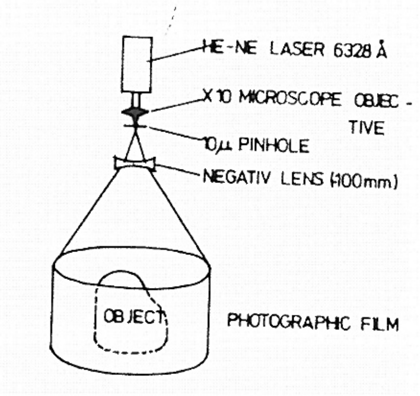


Fig. 5. Jeong's approach

As a consequence, that part of the conical laser beam, which was not reflected by the object in the center of the cylinder, hit the film and served as the reference background. The so recorded and developed cylindrical hologram can be reconstructed either with a sodium or mercury lamp, having a well chosen pinhole, as shown in the schematics of Fig.6,

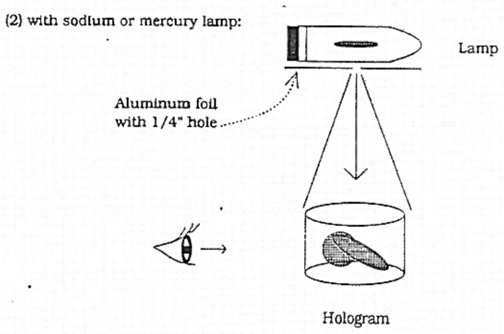


Fig. 6. ODH reconstruction with mercury lamp.

or with laser light. (Fig. 7)

To achieve reconstrucion, one uses either a parallel laser beam which hits a ground glass so that the reconstruction is performed with scattered laser light, or a diverging laser beam. In the latter case, the reconstruction is sharper, however, the viewing angle is restricted.

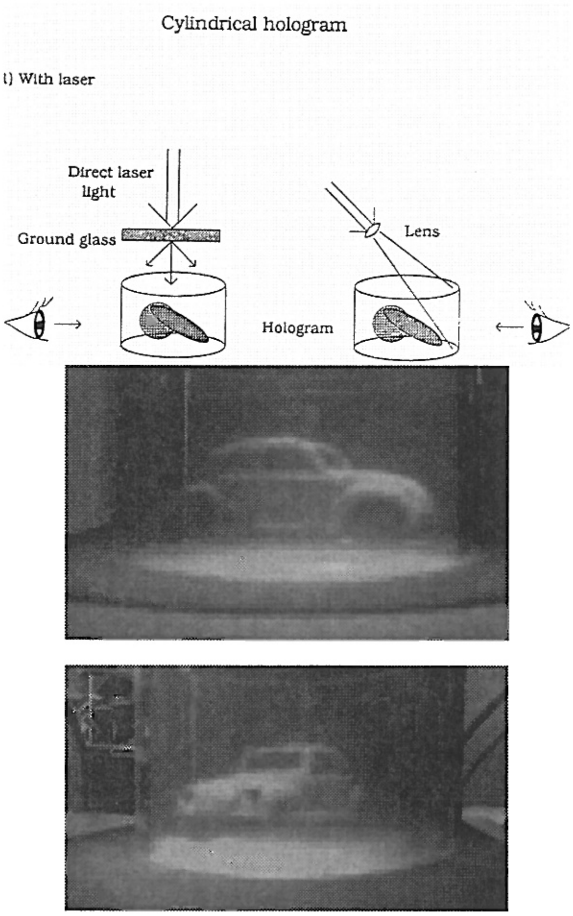


Fig 7. Jeong's ODH (1967) of a toy car, reconstructed from two different viewing angles with laser light, using ground glass technique.

The combination of Jeong's above mentioned method with silver ball technique of Hioki and Suzuki resulted in an ODH that can be reconstructed with white light, since it is basically a Denisyuk-type cylindrical hologram. In this case the diverging laser beam is reflected from a silver ball, and passes through the cylindrical film that faces with its emulsion side the objects placed in the center of the cylinder. To prevent that unwanted light reaches the object of interest, a cover is placed on the top of the cylinder. (Fig. 8)

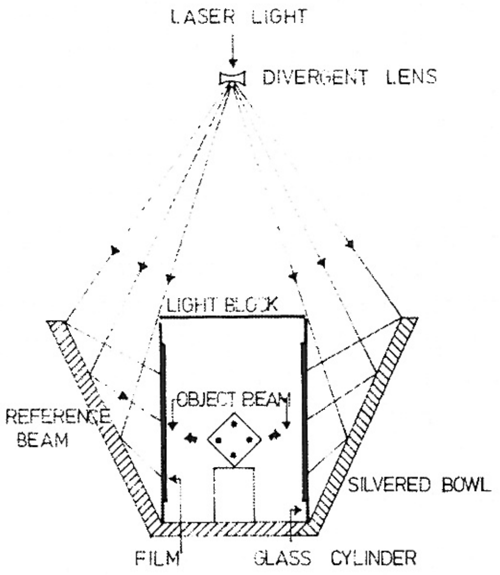


Fig. 8. Recording of a white-light ODH, according to S. H. Hsue et al. (1976).

To get rid of the mirrors that may cause image degradation, Jeong proposed to replace the cylindrical film by a conically shaped film, and illuminate the setup by a conical laser beam from the top, as shown in Fig. 9.

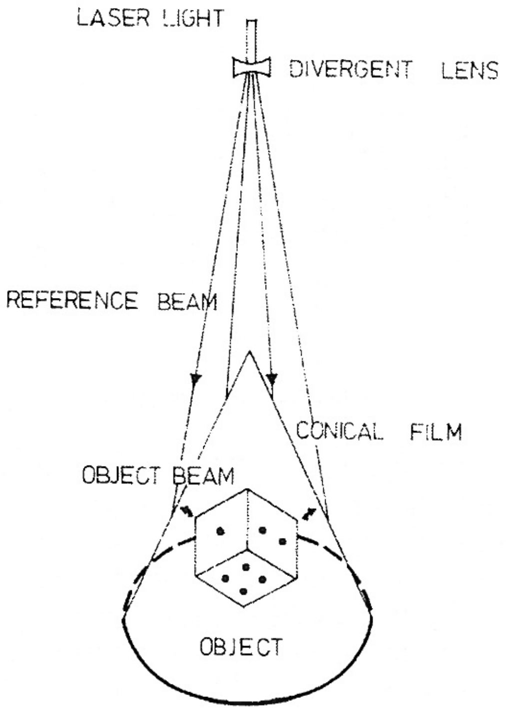


Fig. 9. Recording of a white-light ODH without the use of mirrors.

Hansen's (1988) approach to ODH was based on a construction geometry exploiting various possibilities offered by Benton's rainbow holography:

a) one-step rainbow configuration,
b) simple-beam two-step configuration,
c) two-beam two-step configuration,

where the recording medium used was flat. A ring shaped aperture or a flat ring shaped master hologram produced rainbow viewing window, a truncated cylinder which floats above and around the horizontal holographic image. One typical construction geometry is shown in Fig. 10.

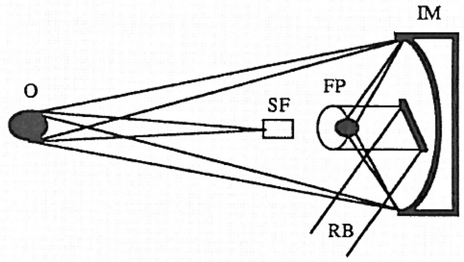


Fig. 10. Construction geometry for one-step rainbow ODH.
O = object, SF = spatial filter, FP = film plane, RB = reference beam, IM = imaging mirror.

The resulting rainbow ODH is viewable in white light from 360°. A cylindrical rainbow window image floats above and around the horizontally displayed hologram. The viewer must look through this rainbow window to see the holographic image, as shown in Fig. 11.

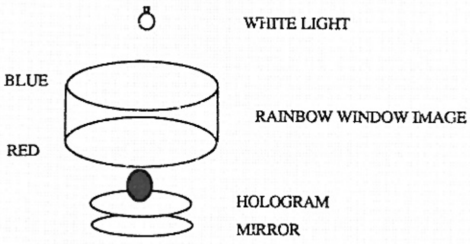


Fig. 11, White light reconstruction of rainbow ODH.

The color of the perceived holographic image is determined by the line of sight from the viewer through the rainbow window image to the hologram.

The various ODH recording techniques described sofar have limitations, which prevent them to be used in fields of holography other than display holography. With the introduction of the new CMI block, the Panoramic Annular Lens (PAL), new vistas are opened in holographic metrology.

Panoramic Annular Lens (PAL)

CMI imaging systems have been known since Mangin (1878), and more than hundred patents have been filed in this topic. The PAL (Greguss, 1983) concept is to combine simply shaped refractive and reflective surfaces in such a way that a *single block* of these optical surfaces provides a *virtual* annular image from the cylindrical space surrounding its optical axis. Depending upon the shape and number of these surfaces, upon the relative position of these surfaces to each other, further, upon the refractive index of the material it is made from, several configurations can be conceived. Using only a combination of four surfaces, each of which may be flat, concave, or convex, theoretically 81 configurations may exist. It turns out, however, that only a few of these configurations are suitable to solve a given imaging task. Fig. 12 shows five out of the 81 possible shapes, which all are characterized by a reflecting or partially reflecting front surface.

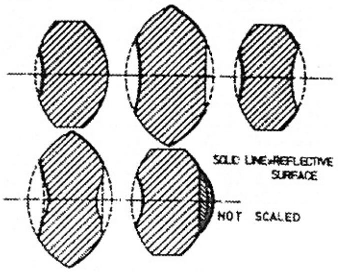


Fig. 12. Various possible PAL shapes (not scaled).

An important characteristic of PAL is that it is almost afocal, and it renders a ring shaped panoramic image from right up against to the lens surface out to infinity.

Further, a very useful feature of PAL is that the width of the resulting annulus represents the viewing angle of the PAL in its optical axis, thus, each pixel along the radii of the projected annular image represents the direction of the object point in space, i.e., the azimuth value of this object point is quantitatively given in degrees or GONs. So, e.g., touching with the cursor arrow the top of the Eiffel Tower (shown in Fig. 13), the elevation value is immediately available

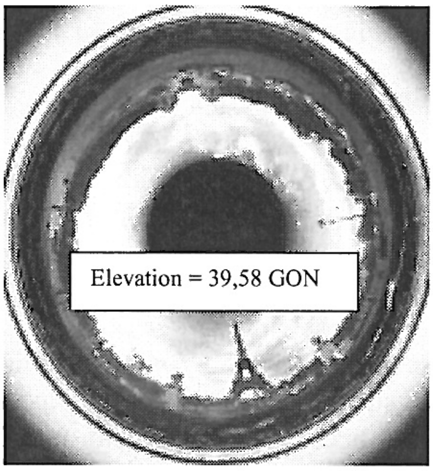


Fig. 13. Displaying the elevation of the top of the Eiffel Tower in GON units.

Knowing the height of the Eiffel Tower (352 m) one can easily determine, by using simple trigonometric functions, the location (P) from where the picture was shot. (Fig. 14)

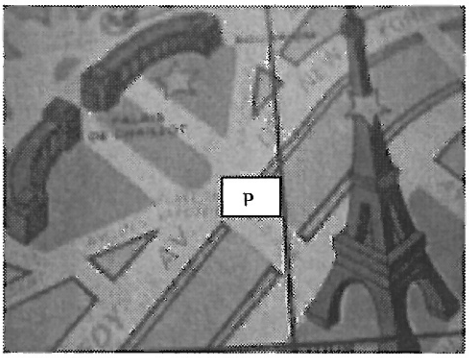


Fig. 14. The spot P from where the PAL picture of Fig. 13 was shot.

From the point of view of ODH, the most important characteristic of a well designed PAL is that, if its flat side is illuminated with a parallel light beam, the light will exit the optic and form a perfect cylinder around the imaging block, and its height will vary with the distance from the optical axis. (Fig. 15)

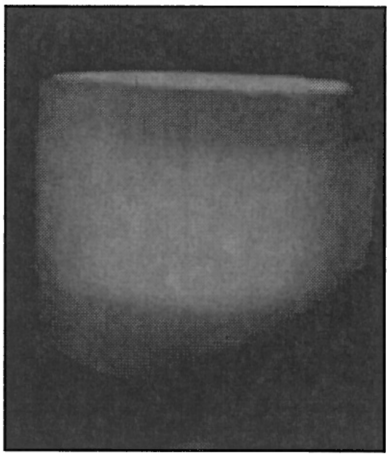


Fig. 15. A PAL illuminated with a parallel light beam creates a light cylinder around its optical axis.

If now a cylindrically formed holographic film is placed around the PAL with its emulsion side looking outwards, rather than in the direction of the PAL, the emerging cylindrical laser wavefront passes through the film and, when reflected from the objects placed in the space surrounding the PAL, will act as an object wave. (Fig. 16)

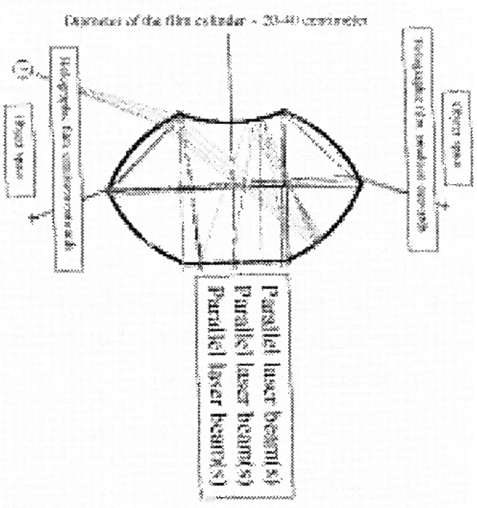


Fig. 16. Schematics of ODH using PAL.

At the surface of the film it interfers with the incoming cylindrical wavefront, and, as a result, an omnidirectional Denisyuk-type hologram is formed, which can be reconstructed with white light. Fig. 17 shows, from two different viewing points, such a panoramic reconstruction of small toys placed around the ODH camera.

Fig. 17. PAL-based ODH reconstructions from two different viewing angles..

A drawback of this configuration is that the object must not be too far from the film, and it should be rather reflective as the reference beam is attenuated as it passes through the emulsion. Otherwise, little object light will be available to expose the film, and the reference beam/object beam ratio becomes non-adequate.

Fortunately, this disadvantage can be eliminated if one exploits that the center region of the PAL [5] around its optical axis does not take part in the forming of the panoramic image; it allows only the image forming rays to pass through. If, namely, a small portion of the front reflecting surface around the optical axis is removed, PAL becomes transparent in its optical axis. (Fig. 18) Consequently, the central part [10] of the collimated laser beam [4] will pass through the optic without distortion, and if a cylindrical or conical mirror [11] is placed at some distance from the optical axis, it will provide an auxiliary illumination for the space surrounding the optic. Thus, this configuration allows the ratio of the object beam/reference beam to be carefully controlled by using neutral filters in the path of the central laser beam [10].

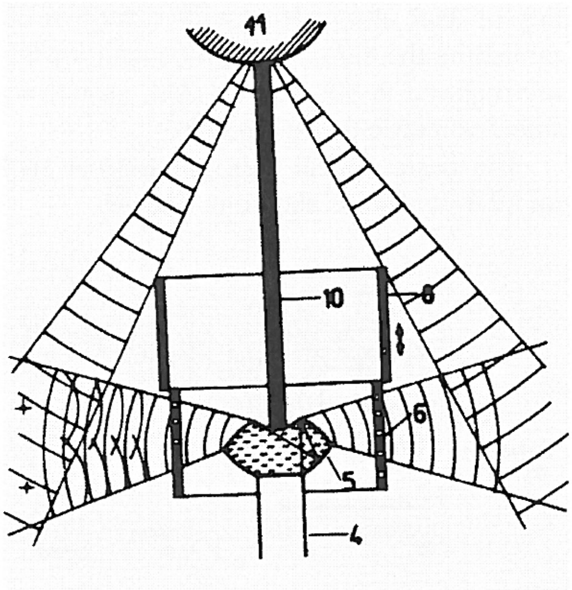


Fig. 18. Controlling the object beam/reference beam ratio in PAL-based ODH.

ODH metrology

Endoscopes are used for visual inspection of cavity interior surfaces. They have, however, a severe drawback: to obtain a real 360° view, i.e., to get omnidirectional optical information, they have to be turned 360° around their optical axis. This means that there will be a *time lapse* between the different field-of-view chunks, which then may cause problems in the correct interpretation of the data obained by this non-contact optical sensor.

The ENDOPAL, an endoscope using PAL as imaging block, solves this problem since it renders a panoramic view in one *single* shot. (Greguss, 1985)

With the discovery of lasers, the metrological possibilities offerred by holography opened new vistas in nondestructive testing (NDT): holographic metrology and speckle metrology emerged. However, these techniques are adequate only to study the *outer* surface of structural components, and not for measurements of the *interior* surfaces of cavities. To extend the metrology techniques mentioned above to NDT of cavities, Greguss (1986) proposed to use ODH. This proposal was picked up by Gilbert (1990) and Matthys (1995), and at present a small group with the Consortium for Holography, Applied Mechanics, and Photonics, University of Alabama in Huntsville (2000) is establishing the parameters and equations that are required to build a dual PAL system for interferometric measurements.

The basic optical configuration of such an ODH system is shown in Fig. 19.

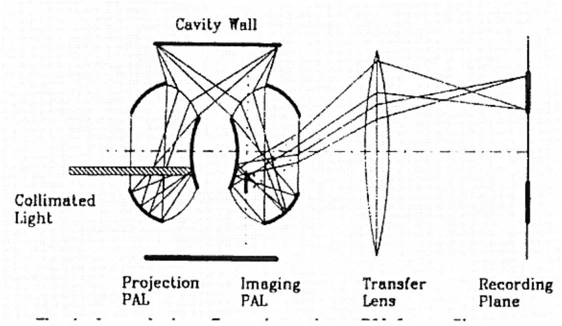


Fig. 19. Basic optical configuration of a twin ODH setup.

A light cylinder emerging from one of the two opposing collinear PALs illuminates the cavity in 360° when collimated light passes through that optic. The second PAL picks up the scattered light and transmits it through a relay lens to the recording surface, e.g., to a CCD camera. (Fig. 20)

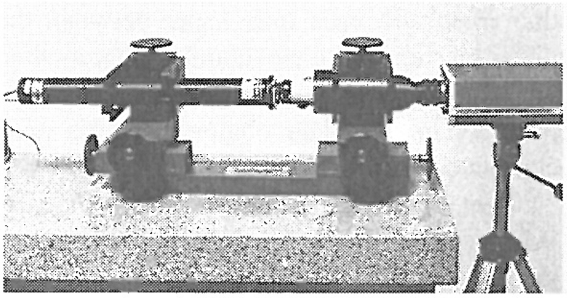


Fig. 20. Realization of a twin ODH setup.

The illuminating source, a HeNe laser, produces panoramic speckle interferometric fringe patterns from the inside of a pipe. (Fig. 21)

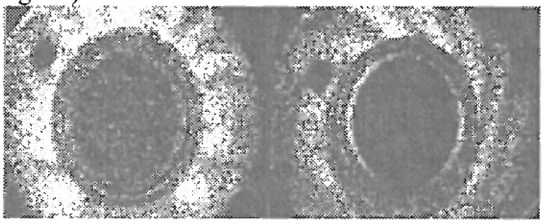
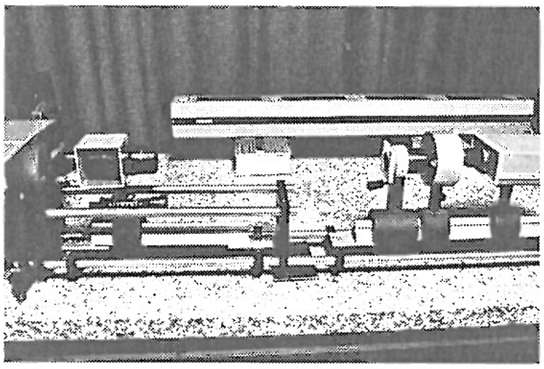


Fig. 21. Omnidirectional speckle interferograms recorded in a tube with a hole in the wall, under two different loading conditions.

However, speckle metrology can also be performed with white light if a speckle pattern is projected onto the surface to be investigated, as shown by Gilbert et al. (1986). This holds also for omnidirectional speckle interferometry, only the laser source has to be replaced by a slide projector and a slide with random speckle patterns. (Fig. 22)



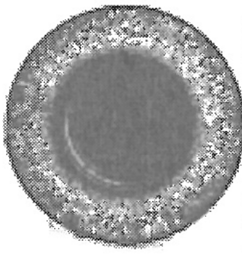


Fig. 22. Random speckle pattern projected by a slide projector onto the wall of a pipe shows up as a PAL picture on the target of the CCD.

Conclusions

Attempts have been made here to give a more-or-less complete overview on the various efforts to develop omnidirectional holography. It had to be emphasized that ODH may play an important role in the various branches of holographic metrology, especially, if a simple CMI block such as the PAL is used to provide those coherent wavefronts that are needed for this kind of noncontact measuring technique.

Finally, one should pay attention to the possibility of developing an omnidirectional waveguide holocamera (Piukovics, 1993), since, if realized in the future, it could be used to investigate the behavior of the outer surfaces of crystals under microgravity conditions. (Greguss, 1997)

Acknowledgements

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