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Holographic interferometry for the study of liquids

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Abstract

Holography is an optical technique enabling to record phase objects. Holographic interferometry uses this faculty to make a phase object interfere with a memory of itself at a preceding time, recorded on a hologram. Interference fringes therefore inform on any variation of the phase of the object. For the study of liquids, these phase changes can result from the evolution of temperature or concentration (via the index of refraction). This access to the real-time evolution of concentration can be used to measure diffusion coefficients, Soret coefficients or dissolution coefficients. Temperature fringes can be used to study convective flows.

Keywords: Holographic interferometry; Liquids; Diffusion

1. Introduction

The expression "holographic interferometry" has a double etymologic origin: "holography" derives from the Greek words $o\lambda o\varsigma$ and $\gamma\rho\alpha\phi\epsilon\iota\nu$, meaning "to write all", whereas the term "interferometry" comes from the Latin words *inter*, *ferire* and *metrum*, meaning literally "a measure of the hits inbetween". We are going to try, along this article, to give a more explicit definition of this powerful optical technique.

Holography was invented in 1948 by Dennis Gabor (1900–1979), a Hungarian-British physicist, just before its arrival at the Imperial College in London. His first motivation was the reconstruction of wave front in electron microscopy [1]. He received the Nobel prize in physics in 1971 "for his invention and development of the holographic method".

But the burst of the possible applications of holography appeared in optics. Leith and Upatnieks, from the Radar Laboratory of the University of Michigan, benefited from the recently developed laser technology to achieve the reconstruction of light wave front, thus enabling three-dimensional photography in 1962 [2].

In the following, we will first describe briefly the basic concepts of holography and holographic interferometry and then focus on known applications of this technique to the study of transparent liquids properties.

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2. Principle of holographic interferometry

To choose a model of light waves relevant for the description of holography, the following approximations are made. The frequency of light ($\sim 10^{15}$ Hz) is not accessible to classical detectors, which measure time-averaged values, so a timeless model is enough. Monochromatic light will be needed, so a one-wavelength model is considered. Linear polarization is preferable, so a scalar representation is sufficient. Therefore, to understand the basic principle of holography, light can be viewed as a mere complex amplitude $U = A\ \exp(i\phi)$, with A the real amplitude and ϕ the phase. This phase is linked to the optical path length δ via $\phi = 2\pi\delta/\lambda$ (λ being the wavelength of the light source). The optical path length contains information on the transmitting medium: $\delta = n \times e$ (e the depth and n the index of refraction).

Classical optical detectors like eyes or cameras are solely sensible to the light intensity $I = \epsilon v|U|^2 \sim |U|^2 = A^2$ (ϵ the permittivity and v the wave velocity). So the phase cannot be registered and the information it contains is lost by these sensors. Therefore, indices of refraction and 3D vision are not accessible directly with photography, video, …

To remedy this lack, Gabor has appealed to Young's theory of interference. The main idea of this theory published in 1801 lies in the fact that when two beams superimpose in one point, their complex amplitude must be summed up, not their intensity, as thought before. This explains that a combination of lights can result in darkness. Therefore, in the case of two beams of complex amplitudes $U_1=A_1\ \exp(i\phi_1)$ and $U_2=A_2\ \exp(i\phi_2)$ crossing in one point, the resulting intensity is $I\sim|U_1+U_2|^2=A_1^2+A_2^2+2A_1A_2\ \cos(\phi_1-\phi_2)$. One notices that this expression includes a $\phi_1-\phi_2$ term, thus containing information on the phases. So if the phase of one of the two beams is known, the other can be deduced. Here lies the basic principle of holography: the detector is illuminated by the beam coming from the object plus by a reference beam with a known phase. Thereby the recorded interference pattern contains the phase difference $\phi_1-\phi_2$ between the two beams, and so informations on the index of refraction and 3D topography of the object [3]. Classical holography is performed in two steps:

A recording step A photographic plate is illuminated by the object beam and a reference beam (generally a plane or spherical wave) of a coherent light. The interference pattern between the two beams is recorded through grey levels on the plate and is called the hologram. This pattern contains a 'coding' of the object phase.

A reconstruction step The object is removed and the plate is developed and illuminated by the reference beam only. The diffraction of the reference beam by the interference pattern on the plate provides a 'decoding' of the recorded object phase. Therefore, when observing through the hologram, a 3D picture of the object can be viewed. A hologram should be viewed as a hole in a wall behind which the object stands rather than as a photograph. For instance, if the plate is broken in two parts, the whole object can still be observed with each part of the hologram alone but with different angles of view, like when hiding half of a hole in a wall.

Holographic interferometry uses the opportunity of recording phase objects to make an object interfere with a memory of itself at a preceding time (registered in the hologram). According to Vest [3], the application of holography to interferometry was first suggested by Horman [4] and Gabor et al. [5] and developed simultaneously in several laboratories during the year 1965. The first application of this technique to fluids was the visualization of gas flows [6]. The experiment proceeds as follows:

- At a reference time t_0, the investigated object is illuminated with the object and reference beams and the hologram is recorded.
- Subsequently both the reference beam – in order to obtain the reconstruction of the object wave at t_0 – and the object beam – creating the object wave at time t – are switched on briefly (double exposure holographic interferometry) or continuously (real-time holographic interferometry). At the object position, one can then virtually find both the illuminated object at present time and its 3D memory at t_0, reconstructed by the diffraction of the reference beam by the hologram. If a change in the optical path length has occurred, interference fringes appear (cf. Fig. 1). This optical path length evolution may result from a motion of the object or from a modification of its index of refraction due to a change in a thermodynamic parameter. So a real-time map of the temperature, concentration, pressure, stress, … can be deduced from the fringe pattern [3].

This technique is less experimentally demanding than classical interferometry because all optical defects between the laser and the hologram (except in the optical cell) remain unchanged at time t_0 and t, and therefore compensate. Furthermore the data analysis is straightforward.

But it should be mentioned that, like for all interferometry measurements, the initial conditions – recorded in the reference hologram – must be reliably known. Indeed interferograms give only informations on the evolution of the system since these initial conditions.

Nowadays, classical holographic interferometry is progressively supplanted by digital holographic interferometry [7]. In this alternative technique, the holographic plate is replaced by a Charge-Coupled Device (CCD) camera. During the recording

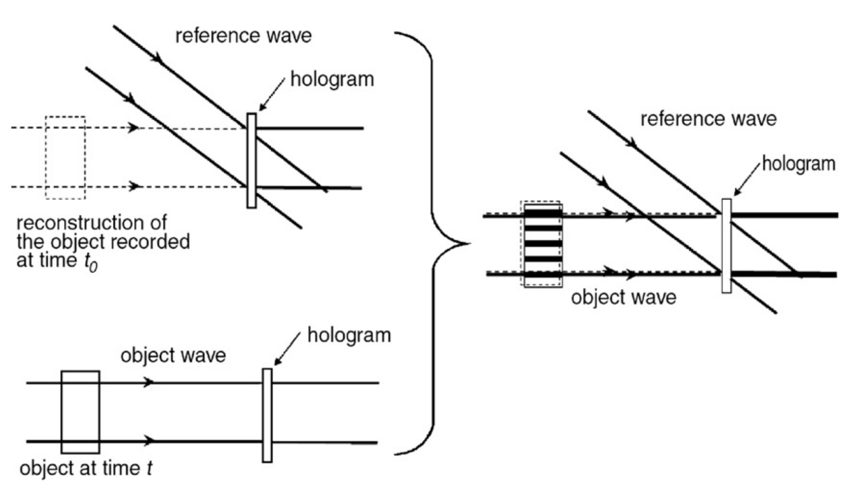

Fig. 1. Schematics of holographic interferometry principle.