On the elimination of DC in reconstructed wavefronts from in-line holograms*

S V PAPPU† and S ANANDA RAO

Department of Electrical Communication Engineering, Indian Institute of Science, Bangalore 560 012

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Abstract. New experimental results to demonstrate that the annoying DC in the reconstructed wavefronts from in-line holograms could be successfully eliminated are presented in this paper. The complete elimination of DC has been achieved by making proper use of a Mach-Zehnder interferometer. The results for an in-line hololens and an in-line Fourier transform hologram are discussed.

Keywords. In-line hologram; DC; hololens; fourier transform hologram; Mach-Zehnder interferometer; positive and negative hologram.

1. Introduction

The in-line method of recording holograms is more or less abandoned while preferring the off-line method for its proven advantages. Of course the nagging problems of in-line holograms viz., the twin images and the DC appearing along the same axis with the real image, render them ineffective for any application (Collier *et al* 1971; Leith and Upatnieks 1962). But the interesting question is: Can an in-line hologram be more useful than an off-line hologram if the unwanted DC and the twin image problems are solved? The answer appears to be in the affirmative in the context of some important application areas such as holographic optical elements (HOE's).

Research and development activities in the field of HOE's have been gaining momentum in recent years in view of the fact that HOE's can be made to be free from aberrations and that with such elements it is possible to build relatively inexpensive large aperture and light weight optical systems. A fair amount of literature on the fabrication and the utilisation of HOE's already exists (Gabor 1967; Close 1975; Schmahl and Rudolph 1976; Mosyakin and Skrotskii 1972; Moran 1971; Richter and Carlson 1974; Manjunath and Pappu 1975, 1976; Manjunath 1976; Mehta *et al* 1977). As a rule, more or less, the off-line method of recording has been used so far in the fabrication of HOE's. However, it is a fact that the level of aberrations in an off-line HOE can in general be higher than that in an in-line HOE (Close 1975). In the light of this fact it appears worthwhile to prefer an in-line HOE for any application and this becomes possible only if the twin image and the DC problems are solved.

Several attempts have been made in the past for the elimination of twin image and

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†To whom all correspondence should be addressed.

DC (Bragg and Rogers 1951; Kirckpatrick and El Sum 1956). These attempts, however, did not yield successful results. While the twin image does not pose any serious threat to the effective utilisation of the real image from in-line holograms such as hololens and Fourier transform (FT) hologram, the DC however corrupts the real image very badly (see for example figure 1a where the real focus from a hololens is obscured by DC). Hence it is necessary to eliminate DC from such in-line holograms and to the best of our knowledge ours is the first successful attempt in this regard. We have achieved the DC elimination by making use of a Mach-Zehnder interferometer in its mode of operation as used for studies on image subtraction (Bromley *et al* 1971; Ebersole 1975). It should be mentioned here that Mach-Zehnder set-up has been used in the past with limited success in the elimination of DC from optical Fourier transformer (Felstead 1971) and coded aperture imagery (Barrett *et al* 1974; Price and LeRoy 1976).

Experiments have been conducted for the elimination of DC in the following two types of in-line holograms: (1) Hololens (i.e., a point source hologram); (2) Fourier transform hologram (i.e., FT Hologram). It is emphasized here that in addition to the achievement of successful elimination of DC in these two kinds of holograms, it has been demonstrated for the first time that (a) positive and negative hologram pair could be constructed in one shot and (b) an in-line FT hologram could be constructed rather effortlessly.

2. Principle of elimination of DC in in-line holograms

It is well known that a circular aperture and a circular opaque disc of identical dimensions give rise to similar diffraction effects, except for the difference that a phase change of π occurs between the various diffraction orders excluding in the region of the geometrical shadow (i.e., the zeroth order). This situation has come to be referred to as the violation of Babinet's principle (Rousseau and Mathieu 1973).

A hologram is basically a zone plate possessing both dispersive and imaging properties and it is termed as positive or negative depending upon whether the central zone is transparent or opaque (Tipton *et al* 1974). It is interesting to note that in the light of these facts the diffraction effects from a positive and a negative hologram could be expected to be similar to the diffraction effects from a circular aperture and a circular opaque disc respectively. This implies that in so far as the zeroth diffraction orders from the positive and the negative holograms are concerned the Babinet's principle is violated and hence one can exploit this fact in the configuration of a suitable interferometer (e.g. Mach-Zehnder) to eliminate DC from in-line holograms. The methodology of elimination of DC is as follows.

The two arms of a Mach-Zehnder interferometer (see figure 2a) are adjusted for an optical path difference of $(2m+1)\lambda/2$ where m is an integer. The positive and the negative holograms are symmetrically located in the two arms in such a manner that at out-gate 1 we could get the two DC's to interfere destructively and thus cancel each other. The two first order diffracted beams, however, would interfere constructively because to the phase difference of π between the two diffracted beams is added another π phase difference by virtue of the experimental set-up making the total phase difference 2π .

Figure 1. Reconstructed image of the real focus from a hololens. (a) Reconstructed focus obscured by DC. (b) Reconstructed focus after the elimination of DC.

Figure 3. Zero fringe image obtained from the Mach-Zehnder set-up. A half fringe is shown to accentuate the impact of the picture.

Figure 4. Reconstructed images from a Fourier transform hologram. (a) Original object; (b) Reconstructed image with profuse DC; (c) Reconstructed image after the elimination of DC.

Figure 2. Mach-Zehnder interferometer set-ups. (a) General set-up used for the elimination of DC. BS₁, BS₂: Beam Splitters; M₁, M₂: Front silvered mirrors; H_p, H_n: Positive and Negative holograms; F: Photographic film. (b) Set-up used for the construction of positive and negative hololenses. L: Lens; P₁, P₂: 10E75 AGFA holographic plates. (c) Set-up used for the construction of positive and negative Fourier transform holograms O: Object transparency; L: Lens used for the construction of FT hologram; P₁, P₂: 10E75 AGFA holographic plates.

3. Experimental

A Mach-Zehnder interferometer is assembled as shown schematically in figure 2 using the following components:

- A 0.5 mW spectra physics model 155 He-Ne or a one watt coherent radiation argon ion laser.
- Front silvered mirrors M₁ and M₂ made of borosilicate crown glass and of the following specifications: Dia 75 mm; thickness 10 mm; surface finish $\lambda/10$ obtained from Hudson Engineering, USA.
- Beam splitter BS₁ (25 × 25 × 25 mm) Type No. 335530 and BS₂ (50 × 50 × 50 mm) Type No. 335550 obtained from Spindler and Hoyer, West Germany.

The two arms of the interferometer are adjusted with the usual care to get a zero fringe (see figure 3) over a desired area, which in our case is a circular area of about 2.5 cm dia. Since the elimination of DC crucially depends on the achievement of zero fringe state for the interferometer, it is surmised that previous attempts of others (Felstead 1971; Barrett *et al* 1974; Price LeRoy 1976) have failed because presumably they did not get the zero fringe over a sufficient area.

4. Results and discussion

4.1. Construction of positive and negative holograms in one shot

4.1.1. *Hololens*: The hololenses used in our study are made by mixing a spherical and a plane wavefront. These two types of wavefronts are generated in the format of a Mach-Zehnder set-up as shown in figure 2b, so that the positive as well as the negative lens can be constructed in one shot at the out-gates 1 and 2 respectively. Usually these are made by taking recourse to the cumbersome conventional photographic replication techniques, which have their own drawbacks (Harris *et al* 1965; Brumm 1966; Urbach 1965). Our method ensures that the positive and the negative holograms are produced under identical conditions.

It is ensured that the positive and negative hololenses have the same focal length and fringe contrast by locating the recording plates equidistant from the lens L in the set-up shown in figure 2b.

4.1.2. *FT hologram*: As mentioned earlier we have constructed successfully an in-line FT hologram. It is believed that no attempts have been made to construct in-line FT holograms in the past because of the fact that they contain the annoying DC.

The in-line positive and negative FT holograms used in our experiments have been constructed using a modified Mach-Zehnder set-up as shown in figure 2c.

4.2. Elimination of DC in hololens

The positive and negative hololenses constructed by the method described above are located symmetrically in the two arms of the Mach-Zehnder set-up shown in figure 2a, after it is adjusted for zero fringe. By proper adjustment for π phase difference the DC could be completely eliminated and the focal spot from a hololens without the annoying DC is shown in figure 1b. By comparing the results shown in figures 1a and 1b it is evident that the clean focus of an in-line hololens can easily be obtained by proper utilisation of the Mach-Zehnder set-up. It is suggested here that the elimination of DC from the reconstructed wavefronts of hololenses as described here could be used in making the Mach-Zehnder set-up an integral part of an all hololens coherent optical spatial frequency processor, whereby the in-line type hololenses can be deployed exploiting their inherent advantages.

4.3. Elimination of DC from in-line FT holograms

As can be expected the reconstructed image from an in-line FT hologram is marred by the presence of profuse DC. We could successfully eliminate it by employing the same method that is used in the case of hololens. The original object, the reconstructed image with DC and the image after the DC removal are shown in figure 4.

5. Epilogue

The results of this study conclusively prove that the annoying DC from in-line holograms could be eliminated completely by making proper use of a Mach-Zehnder

interferometer. The DC elimination allows us to take the full advantage of the desirable characteristics of in-line holograms for any application.

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