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Experimental study of frequency response in digital holography

Nazly Hincapie, Jorge Garcia-Sucerquia*

Universidad Nacional de Colombia, Sede Medellin, School of Physics, A.A. 3840 Medellin 050034, Colombia

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ABSTRACT

In this paper, we present an experimental study of the frequency response in off-axis numerical reconstruction of digitally recorded holograms (DH). Despite of the fact that several works have reported the way how the digital holographic imaging systems deal with the frequency of the imaged objects, all of them are limited to computer modelling. Up to the best knowledge of the authors this is the first attempt to experimentally evaluate the response on frequency of DH. A star test of resolution is imaged in DH to measure the modulation transfer function (MTF), which is quantified as the ratio of the contrast of the reconstructed image over that of the input object. From the measured MTFs, trade-off guides in terms of the frequency response of the DH imaging system can be elaborated as the reduction of data to be processed or data-compressing is of interest.

1. Introduction

Perhaps the most powerful tool to evaluate the performance of an imaging systems is the quantification of its frequency response [1,2]. That quantification is performed by using an input signal with a set of known spatial frequencies and evaluating the spatial frequencies that compose the output signal. This operation allows the identification of well-stablished parameters, as for instance the maximum frequency that the system can process or cut-off frequency, which can be utilized to fully characterize the studied system.

According with the kind of illumination utilized in the imaging system, it can understood as linear in amplitudes for coherent illumination or linear in intensity for the case of incoherent illumination [1]. For the former, the amplitude transfer function tells how the imaging system handles the spatial frequencies. For the latter, the optical transfer function (OTF) is essentially what quantifies the manipulation of the spatial frequencies done by the imaging system. In either case, the result of the evaluation of the frequency response of the imaging system is therefore a function controlled by the spatial frequency of the input signal.

Among the most utilized figures to quantify the frequency response is the modulation transfer function (MTF) [1,2]. Despite the MTF is strictly defined as the modulus of the OTF, its intrinsic meaning allows the understanding of the MTF as the ratio of the contrast of the output signal over that of input signal, namely the transfer of contrast [2]. This extended definition of the MTF has broaden its application to characterized both coherent and incoherent imaging systems, by simply measuring the ratio of the visibilities of the output and input signals.

* Corresponding author.
E-mail address: jigarcia@unal.edu.co (J. Garcia-Sucerquia).

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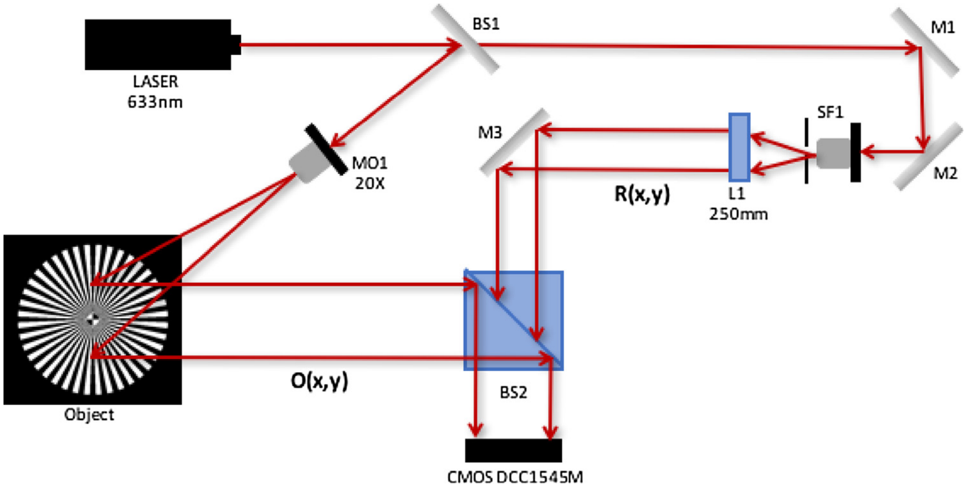

Fig. 1. Digital holography setup. BS: beam splitter, MO: microscope objective, L: lens, SF: spatial filter, M: mirror, O: object wave, R: reference wave.

The numerical reconstruction of digitally recorded holograms, namely digital holography (DH), can be understood as a coherent imaging system for which its frequency response is susceptible of being studied. The very first attempt to fulfill this task was done by Kreis [3]; a point source was theoretically image through the DH system to compute the different metrics that characterize the system. A geometric MTF [4] was numerically evaluated to express the response in frequency of the DH. The interest on understanding the frequency response of DH propelled also the theoretical evaluation of the MTF through the idea of its understanding as the ratio the visibilities of the output and input signals [5]. Further and very detailed theoretical studies of the imaging properties of DH have been published in the specialized literature, that considered very important features as the spatial resolution and speckle noise [6–11].

Despite the great effort that has been done to theoretically include all the parameters that affect the performance of the DH imaging systems, we consider very worth any attempt to experimentally evaluate such performance. In particular, the theoretically evaluated frequency response of DH could be experimentally tested to verify its correctness. Within this realm of study, we have only found one published work that somehow experimentally measured the MTF of DH to quantify the results of a method to reduce speckle noise [12], but no further experimental evaluation of the parameters that theoretically control the frequency response of DH.

In this work, we present an experimental study of the frequency response of the DH imaging system. The MFT of DH, quantified as the ratio of the contrast of the output signal to that of the input signal, is evaluated for different experimental configurations that validate theoretical findings in this regard and provide further trade-off guides for data-reduction and data-compressing in DH imaging system.

2. Numerical reconstruction of digitally recorded holograms (DH)

The numerical reconstruction of digitally recorded holograms, named digital holography (DH), can be understood as a two-stage imaging system. The first stage is the recording of the digital hologram $H(x, y)$ what can be done in a setup like the illustrated in Fig. 1. The digital hologram, i.e. the interference pattern produced by an object wave $O(x, y)$ and a reference wave $R(x, y)$, is recorded on the surface of a digital camera. To guarantee the recording of a steady the digital hologram, $O(x, y)$ and $R(x, y)$ are typically generated from a coherent source like a laser by splitting its light beam; in Fig. 1 that is split is done by the beam splitter BS1. $O(x, y)$ is produced by the propagation to the digital camera of the wave that illuminates the object; MO1 is a microscope objective that expands the laser beam out to fully illuminate the objet to be imaged. $R(x, y)$ is regularly a homogeneous plane wave that impinges perpendicularly on the digital camera, such that its numerical representation is simplified to a constant value. In the setup of Fig. 1, the $R(x, y)$ plane wave is generated by the combination of the spatial filter SF1 and the lens L1; M3 directs $R(x, y)$ to the surface of the digital camera. On considering explicit forms for $R(x, y) = A_R$ and $O(x, y) = A_O(x, y)\, e^{i\varphi_O(x,y)}$, the digital hologram can be written as:

$$\mathrm{H}(x, y) = |R(x, y) + O(x, y)|^2 = |A_R|^2 + |A_o(x, y)|^2 + A_O(x, y)\, e^{i\varphi_O(x,y)} A_R + A_O(x, y)\, e^{-i\varphi_O(x,y)} A_R\,. \quad (1)$$

The angle of superposition between $O(x, y)$ and $R(x, y)$ over the surface of the digital camera determines the recording of the digital hologram: on-axis, for both waves imping parallel, or off-axis for both waves making a non-null angle between them [13]. For the latter case care, must be taken on the selection of the angle to fulfill the sampling theorem [3,14,15] and to optimized the use of the available space bandwidth [15]; further details on the angle selection can be read elsewhere [13,15]. The digitally recorded hologram is then transferred to the memory of a computer to perform the second stage of the DH imaging.