Insect wing deformation measurements using high speed digital holographic interferometry

Daniel D. Aguayo[1,*], Fernando Mendoza Santoyo[1], Manuel H. De la Torre-I[1], Manuel D. Salas-Araiza[2], Cristian Caloca-Mendez[1] and David Asael Gutierrez Hernandez[1]

[1]*Centro de Investigaciones en Optica A. C., Loma del Bosque 115, León, Guanajuato, 37150 México*
[2]*Universidad de Guanajuato, DICIVA, Departamento de Agronomía, Km 9 Carretera Irapuato-Silao, Irapuato, Guanajuato, 36500 México*
**daguayo@cio.mx*

Abstract: An out-of-plane digital holographic interferometry system is used to detect and measure insect's wing micro deformations. The in-vivo phenomenon of the flapping is registered using a high power cw laser and a high speed camera. A series of digital holograms with the deformation encoded are obtained. Full field deformation maps are presented for an eastern tiger swallowtail butterfly (Pterourus multicaudata). Results show no uniform or symmetrical deformations between wings. These deformations are in the order of hundreds of nanometers over the entire surface. Out-of-plane deformation maps are presented using the unwrapped phase maps.

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OCIS codes: (120.0120) Instrumentation, measurement and metrology; (120.2880) Holographic interferometry; (120.4290) Nondestructive testing

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#123510 - $15.00 USD Received 29 Jan 2010; revised 19 Feb 2010; accepted 19 Feb 2010; published 4 Mar 2010

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1. Introduction

Recent advances in non-contact optical techniques which are mainly applied to measure superficial deformations on an object allow indirect detection of its mechanical properties. Most of these techniques have higher resolution than their similar and more traditional mechanical tests [1,2]. Digital holographic interferometry (DHI) is an optical non-contact method which generates qualitative and quantitative information from an object’s displacement [3–5].

DHI has been applied to inspect biological samples as an alternative to traditional invasive techniques [6]. The research reported here stems from the interest of scientists and engineers to design, develop, and improve flying systems. Insect wing flapping may prove to render very useful data that will contribute to better understand the aero dynamical properties of human used aircrafts. Previous studies have helped to gain a better understanding about the structures, the shape and the behavior of winged animals, in particular in trying to reproduce the complex characteristics involved in flying. Most of this knowledge is already applied in modern aerodynamic models which allow more efficient airplanes, rockets, etc [7–9], and has served to enhance physical parameters such as air pressure and friction reduction [10]. In recent years research on flying structures has been primarily focused in newer techniques like computer modeling, new pressure sensors, computational simulation, and flow visualization [11–18].

Further research used and developed nano electronic models with complex computer control systems which simulate an insect’s flight [19–21]. Photogrammetry is yet another useful technique applied to extract the kinematics of several marked points on an insect wing during tethered and hovering flight [22]. In this manuscript, a new approach to the study of insect wing deformation during flight is presented. A DHI system with a high speed camera and a cw high output power laser to record fast and non repeatable events [23–25] to detect very fast wing deformations with interferometric resolution is used. A series of deformation maps during insect flapping are presented and a discussion about the results is presented. This optical non-destructive technique may prove to be an extraordinary alternative to understand the phenomena of insect wing deformation in events such as the up-stroke and the down-stroke movements.

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2. Model

DHI is a remote, non-invasive whole field optical technique based on the interference between an object and a reference beam. The interference intensity signal is recorded by a 2D sensor and an image hologram is thus recorded. In order to observe a relative deformation between two different states of the sample under study it is necessary to compare a reference state with a second one when the object suffers a deformation (viz. ref. 1). The result of this comparison is a wrapped phase map directly related to the object surface deformation. DHI may be applied to quantify parameters such as mechanic vibrations [26], elastic deformations [27], strain [28] and crack detection [29], among many other successful applications. Most systems are designed to have in plane or out-of-plane displacement sensitivity [30]. In both cases, the intensity recorded by the CCD camera sensor can be represented in general form as:

$$I(x,y) = \left|R(x,y)\right|^2 + \left|U(x,y)\right|^2 + R(x,y)U^*(x,y) + R^*(x,y)U(x,y) \tag{1}$$

where x and y are the spatial pixel coordinates, R(x, y) and U(x, y) are the reference and object beam amplitudes, and * denotes the complex conjugate amplitude of these quantities. To obtain the relative phase map between the two object states a Fourier transform and its inverse is applied to each digital holographic interferogram, and upon subtraction of the two inverse transformed images, see for instance ref [31], the resulting relative phase may be found from,

$$\Delta\phi_n = \arctan\left\{\frac{\mathrm{Re}\left[I_{n-1}\right]\mathrm{Im}\left[I_n\right] - \mathrm{Im}\left[I_{n-1}\right]\mathrm{Re}\left[I_n\right]}{\mathrm{Im}\left[I_{n-1}\right]\mathrm{Re}\left[I_n\right] + \mathrm{Re}\left[I_{n-1}\right]\mathrm{Im}\left[I_n\right]}\right\} \tag{2}$$

where $\Delta\phi_n$ is the relative wrapped phase map between a reference state hologram (I_{n-1}) and an n-th hologram (I_n). Re and Im represent the real and imaginary part of a complex number. Finally, the wrapped phase maps are unwrapped using a minimum cost matching algorithm (the commercially available Pv_psua2 from Phase Vision Ltd., was used) which generates a decoded displacement map.

3. Experimental Method

The optical setup configured to measure out of plane deformations is schematically shown in Fig. 1. The object is illuminated with a Verdi laser (Coherent V6), with a maximum output power of 6 W at 532 nm, and is divided into an object and reference beams using a 50:50 beam splitter (BS). The object beam illuminates the insect using a 20X microscope objective which covers the entire insect's surface.

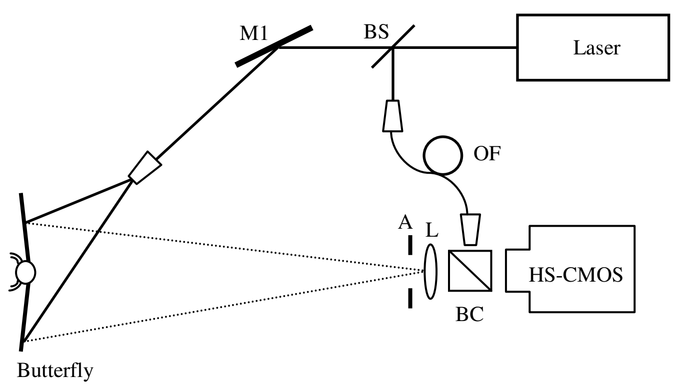

Fig. 1. Schematic view of the experimental set up where a high speed camera is used (HS-CMOS).

The backscattering coming from the object is then collected by means of a 125 mm focal length lens (L) located behind an aperture (A). The reference beam is launched into a single

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mode optical fiber which is combined with the object beam using a 50:50 beam combiner (BC) in front of the camera sensor. In order to observe the entire insect the field of view (FOV) is set to image an area of 90 X 100 mm. The interference between object and reference beams is captured using a high speed camera (NAC GX-1) with an image resolution of 1024 x 1280 pixels at 10 bits dynamic range. The butterfly insect chosen for the purpose of this research is common in the local ecosystem making it easy to capture, and due to the very large numbers found there is no risk related to endangering its specie, which is called Pterourus multicaudata, obtained since it was in pupal stage. A couple of hours after it emerged from the pupa; it has a size of 88 X 130 mm of height and width, respectively.

To perform the in-vivo experimental measurement it is necessary to fix the butterfly onto a rigid surface trying to avoid any damage to it, or indeed minimize the damage. The procedure followed, with the help of an expert on the subject and co-author of this manuscript, was to glue each leg to a dark metal post and to wrap a thread around the insect in two contact points such that it was left free to move its wings. This procedure avoided the need to use a pin through the butterfly which will modify its wing movements and eventually kill it. The butterfly was then minimally affected and its wing flapping may be safely considered motion free. Each experimental test lasted only a few seconds, after which the insect is released and set free.

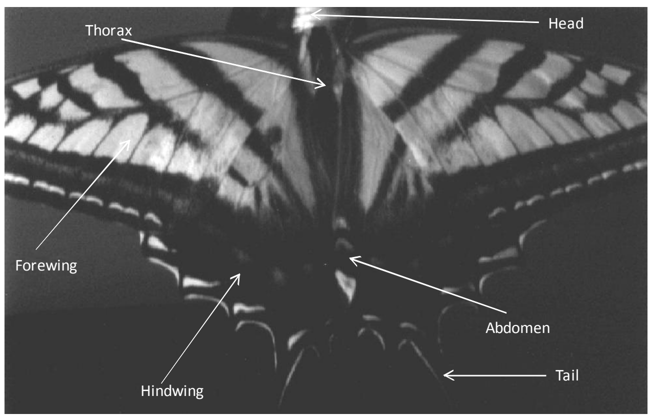

Fig. 2. White light image of the butterfly.

In Fig. 2 an actual image of the butterfly in its position during the test is shown and the main body parts are pointed, to secure natural wing movement no special preparation was used on their surface. Once the insect is in position in front of the imaging system a series of images are recorded at 500 frames per second, which is the ideal CMOS camera repetition rate found to perform the experiments, i.e., the required camera repetition rate to momentarily freeze the wing movement. During the recording process the electronic shutter of the CMOS camera was open, however due to its working characteristics the exposure time is much less than 1 ms. Besides, the flapping frequency is about 15 times slower than the sampling rate of the camera. For the recording the butterfly is freely flapping and the up and down stroke movements are registered.

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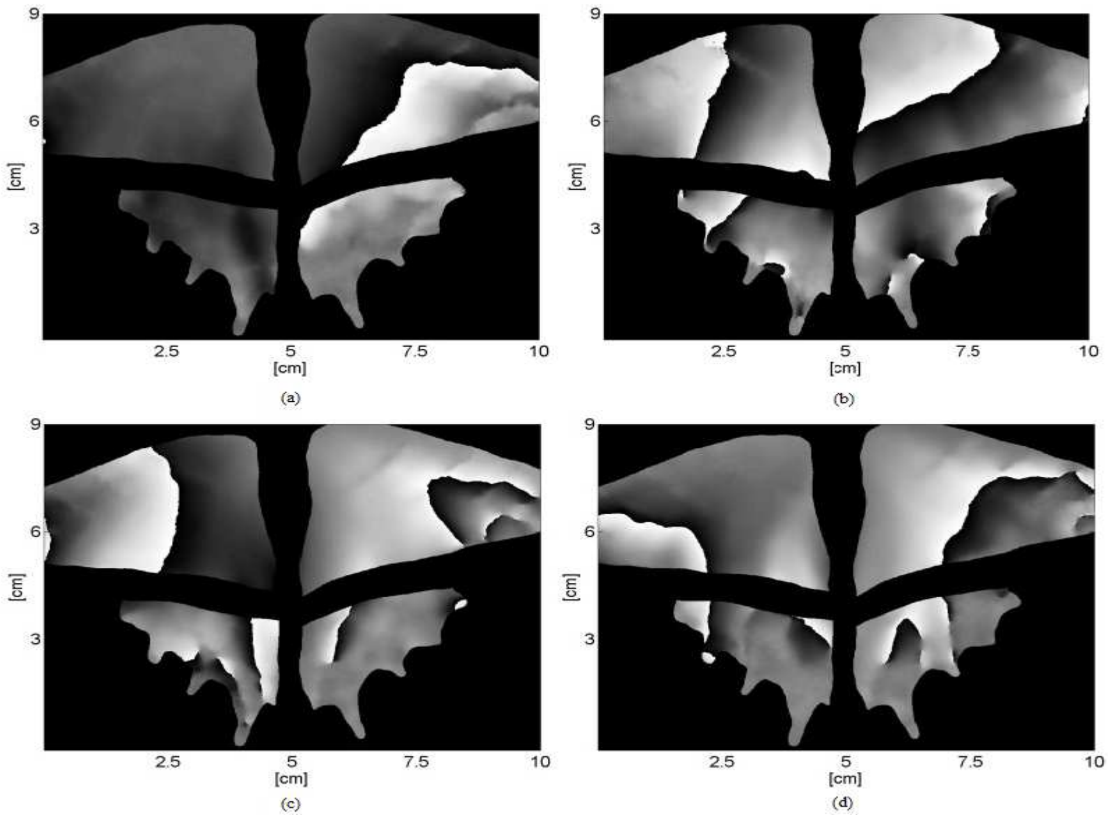

Fig. 3. (a), (b), (c) and (d) (Media 1) show butterfly wing wrapped phase maps during several moments, no specific ones, through flapping motion.

Figures 3a, 3b, 3c and 3d show a series of wrapped phase maps at different, not controlled, instants of the wing flapping. The wrapped phase maps represent variations from -π to π, and represent the insect's wing deformations for non controlled time instants during the flapping. The deformation presented in these figures do not represent the whole amplitude of the flapping movement which has centimeters of displacement, instead the images refer to micro deformations along the wings between any two consecutive images at 500 fps. With this information it is possible to reconstruct the real out-of-plane deformation map when unwrapping all wrapped phase maps. The corresponding unwrapped phase maps are shown in Figs. 4a, 4b, 4c and 4d, where data quantification for the deformation present in the wing's surface during time intervals of 2 ms may be readily calculated. For these figures the displacement range goes from –0.9 µm to + 0.9 µm.

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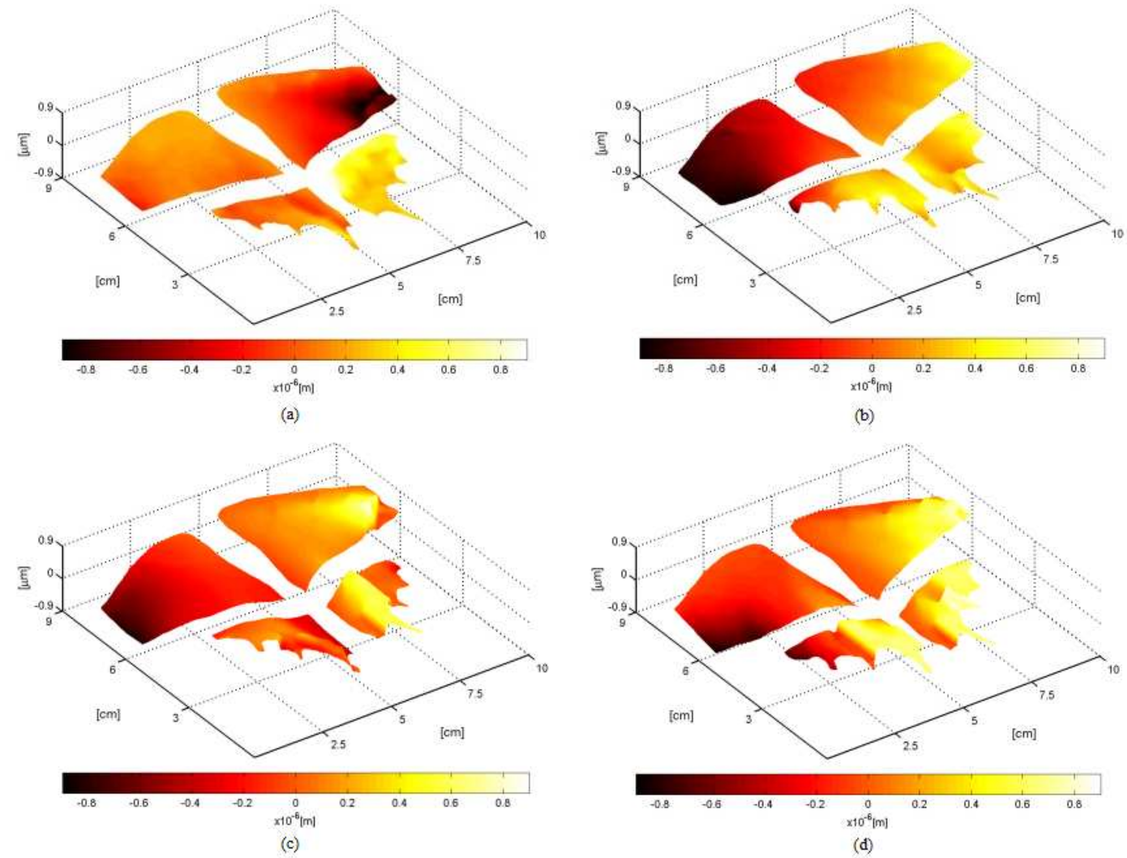

Fig. 4. (a), (b), (c) (Media 2) and (d) (Media 3) represents butterfly wing surface deformation recovered from DHI measuring experiments. The media files show different moments of the flapping during the test and as such are showing a movie of different unwrapped sates.

4. Conclusions and discussion

To the best of our knowledge it is for the first time reported in the internationally available literature the use of an optical technique to observe the full field deformation on butterfly wings during flapping. From Fig. 3 it is possible to observe that the forewing and the hindwing have independent flapping movements, not necessarily symmetric between them. Considering the absence of any treatment in the insect's wings, like the application of white developing powder that will kill the butterfly within minutes of its application, dark regions produce weak scattering which then introduce discontinuities during the unwrapping process (see
Fig. 2). If the dark region on the wing is masked out (a natural dark fringe on the wing), the unwrapping process is greatly improved as can be seen in Fig. 4.

In all experiments we considered the wing as a whole unit, but further study is needed in order to describe the effect of the scales present in the wing, which under close observation have an independent movement from each other. It is important to remark that this is a specific behaviour present in this butterfly under the particular conditions mentioned. The same behaviour should not be expected in every winged insect because it involves the wing shape, insect morphology and the flight conditions. Results show the behaviour for this butterfly (Pterourus multicaudata) which is part of a huge family species. The future study and research on insect wing flapping will render useful data that will no doubt contribute to better

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understand the aero dynamical properties of human designed aircrafts. The advantages of having a high speed camera are showed in this work for non repeatable events, like this butterfly flapping, a feature not possible to observe for the naked or unaided eye, or conventional cameras. This technique has high resolution and high sensitivity at 500 fps without needing any extra data processing to extract the deformation maps.

Acknowledgements

All authors wish to thank the Consejo Nacional de Ciencia y Tecnología (CONACYT, MEXICO) for partially supporting this research through grant No. 42971, and research scholarships for Mr. Aguayo, Caloca and Gutierrez. The invaluable help of Mr. Silvino Muñoz-Solis is hereby gratefully acknowledged.

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