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Abstract. Optical techniques such as speckle pattern interferometry are well known in the nondestructive testing measurement community. They can be used, for instance, as a predictor of the mechanical behavior of a sample under study. However, in almost all circumstances, a mathematical model has to be applied in order to make sense of these measurements. This is a critical issue when an organic sample is studied, mainly due to its complex deformation response. A good example of this is observed in the birds' feathers. They have extraordinary mechanical and aerodynamic properties thanks to their stiffness and lightness. A couple of live birds are safely situated in front of an out-of-plane sensitive digital holographic interferometer (DHI), an optical system capable of recovering the optical phase in this type of nonrepeatable or unpredictable experiment. In order to recover the backscattering signal and its interferometric response, several images are recorded from different sections of the plumage. Displacement maps are obtained from what is, as far as is known, the first time that full field microdisplacement maps are presented over a hummingbird and a parakeet plumage. [DOI: 10.1117/1.JBO.18.5.056011]

Keywords: digital holographic interferometry; organic scattering, physical biology.

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1 Introduction

A small and common backyard bird is a really sophisticated organism who can travel impressive long distances with an extraordinary energy efficiency. They have an impressive innate navigation knowledge which helps them to cross half the terrestrial globe and arrive at the same spot every year.[1] Birds are found in practically every part of the world in a huge variety of colors and sizes.[2] Extensive and wide research studies on this topic have been carried out in order to understand this variety and the way they can sort hundreds of kilometers under harsh flying conditions.[3] This particular fascination for birds is present in the different studies dedicated to them.[4–8] The bird's flight has attracted the attention and imagination of human kind who has dedicated pictures, poems, and the like to sophisticated mechanical devices which tried to reproduce their flight ability. The study of this phenomenon has been developed at different levels of detail along human history. During the last century, we were witness to huge advances in modern aircraft. The general ideas behind this were fuel efficiency, less aircraft wind friction, more reliability, and sharper and more economical designs. But a constant in all these aircrafts was the rigid mechanical parts of which they are made. Recent research works use new models and materials aiming to evoke a more accurate model of natural bird flight.[9–13] However, a critical part of it comes from the feathers that cover their body. The result of thousands of years of evolution is an extraordinary structure which combines stiffness and lightness in one simple but elegant structure.[14,15]

The feather is a complex structure that interacts with air flows, regulates a bird's temperature, and works as an external protective layer.[16,17] There are several studies about the type of feathers and their aerodynamic properties during flight,[18,19] and the way they are microscopically structured.[20,21] Different kinds of feathers have different structures with respect to the role they play. The general response of the feathers has been observed, but a more detailed study of the superficial microdisplacements will provide new information to the overall response of this complex system.

Some works in biological samples involved the use of pulsed lasers,[22] white light,[23] and endoscopes[24,25] to inspect them in full field. There are also techniques which evaluate the average speckle contrast coming from the sample.[26] Nevertheless, by its nature most of the biological samples will introduce noise which requires sophisticated filters to remove.[27] In the research work reported here, a nondestructive optical method to study the micro movement and displacements on the feathers is introduced. The system is based on a two-beam interferometry technique which was successfully applied to observe the surface displacement of butterflies' wings.[28,29] These insects also present a similar feather effect due to superficial scales on their wings which modify among other features such as the manner in which the light scatters.[30] In order to have a real response, no special preparation was done on the feathers. The optical system is able to observe the entire bird or specific sections of its body. The interferometric response depends on the natural movement of the bird and the interaction of the laser light with the different kinds of feathers. For the experiments two different birds are used, a hummingbird and a budgerigar that are common in our environment. No damage was done to the birds, which were inspected by a veterinarian and set free after the short time that the experiments took. As is well known, the hummingbird has a high flapping speed while the budgerigar is a common house pet which is less active.

2 Method

The method to be used is a noncontact or noninvasive optical technique called digital holographic interferometry (DHI) which

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is primarily based on the speckle phenomenon. It was chosen mainly due to its high spatial sensitivity and its ability to record fast and nonrepeatable events. In DHI it is necessary to acquire a couple of interferometric images from an object that has undergone a displacement between the two images. The optical phase between them, i.e., the relative change in optical path, is obtained using a Fourier algorithm.[31] This phase difference can be expressed as

$$\Delta\varphi = \varphi - \varphi', \tag{1}$$

where φ and φ' are the optical phase before and after the deformation, respectively. This results in a fringe pattern which shows equidistant lines along the surface as a result of the deformation. A further process obtains a wrapped phase map which has the displacement information codified within a range of $-\pi$ to π (black and white, respectively). This wrapped map is then unwrapped using an algorithm which obtains a continuous displacement map in radians. Finally, the unwrapped phase map can be associated to a displacement (radians converted to micrometers) with the following scalar expression:[32]

$$\Delta\varphi = \frac{2\pi}{\lambda}(1 + \cos\theta)d, \tag{2}$$

where λ is the wavelength of illumination, θ is the angle between the illumination and the observation directions and d is the real displacement. From Eq. (2) it is possible to recover the physical response of the object under study.[33] Figure 1 shows an example of the latter, a metallic plate is deformed during an interferometric test where it was possible to measure an overall displacement of 1.2 μm.

DHI allows the recording of a full series of images from a nonrepeatable event which is an appropriate feature for an organic study. This technique uses the backscattering coming from the sample which is collected by a lens that conveys it onto a camera sensor. However, if the object under study presents an uneven scattering response, the interference signal will be compromised. Mind you, the latter is a common response when organic samples are studied using coherent light.[34,35] Particularly, the microstructure of the feathers works as an optically rough surface suitable for this technique, however, in some cases they can introduce a diffractive effect.[36] This phenomenon is clearly observed with the naked eye in some

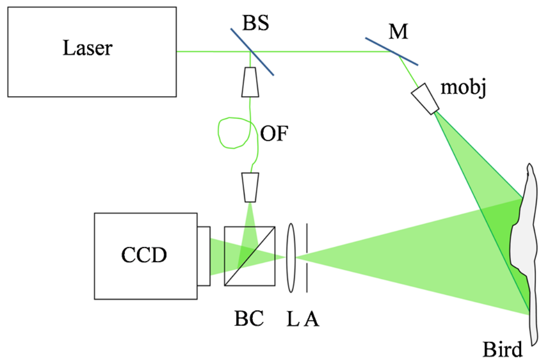

Fig. 3 Schematic view of the DHI setup, where a 20× microscope objective (mobj) and a single mode optical fiber (OF) are used as beam expanders for the object and the RB, respectively. A mirror (M) is used to redirect the OB in the observable section of the bird. BS is a beam splitter, BC is a beam combiner and A is the aperture in front of the lens (L).

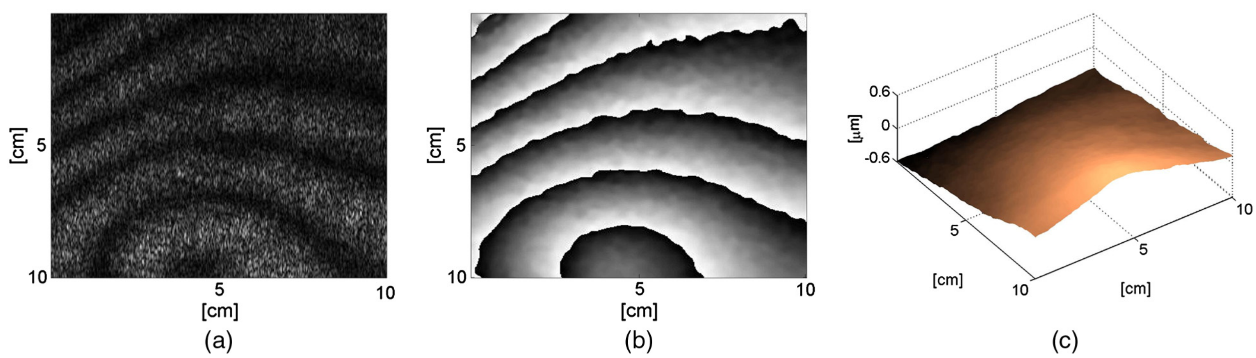

Fig. 1 DHI optical measurement example using a metallic plate; (a) fringe pattern, (b) wrapped phase map and (c) displacement obtained from the unwrapped phase map.

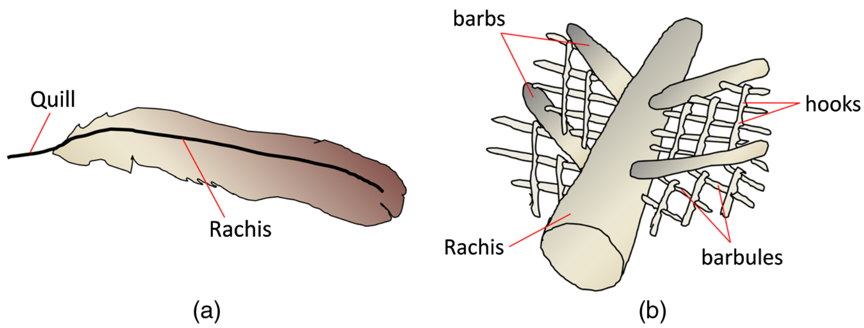

Fig. 2 Schematic view for: (a) primary feather and (b) feather central section.

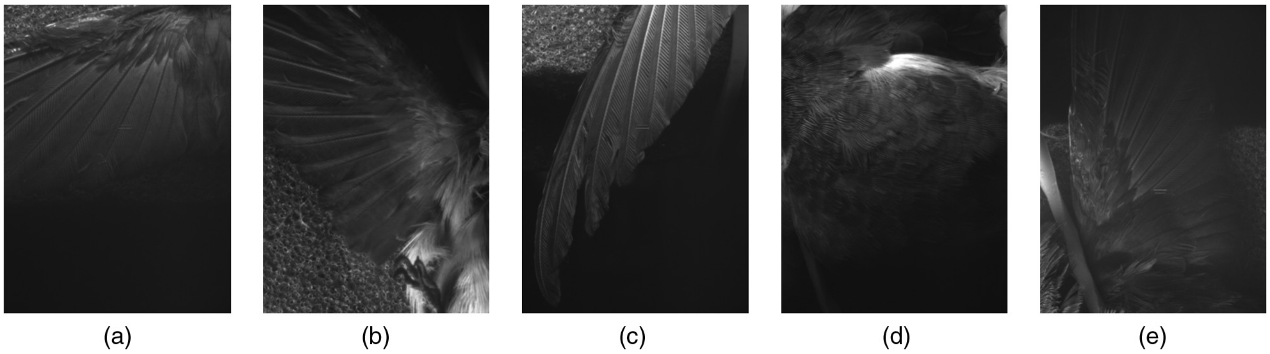

Fig. 4 The hummingbird body sections analyzed with a FOV of $67(h) \times 90(v)$ mm. (a) Under wing primary and secondary coverts, (b) under wing primary and secondary coverts and axillaries, (c) greater under wing primary covert, (d) back, rump and upper tail covert, (e) secondary coverts.

birds that have iridescent and colorful feathers.[37,38] Furthermore, the feathers present different combinations of pigments which can modify the light absorption and therefore the signal response of the interferometric system. Figure 2(a) shows a primary feather that consists of a calamus (or quill), as the section which is physically inserted into the bird's body. Following the quill, the rachis or shaft is found, where several barbs are attached. A dense mesh grid is formed between the barbs by means of the barbules with and without hooks [see Fig. 2(b)]. This particular structure gives an extraordinary mechanical stiffness but also a light construction. The kind of feather and specimen determines the number of barbs and the form in which they are arranged together.

In some birds this barb-barbules structure looks like a bundle where the light can be easily diffracted. This diffraction effect varies when the illumination angle is modified while the observation angle remains fixed.[39] Considering the above, the DHI system proposed here is designed with a large object distance

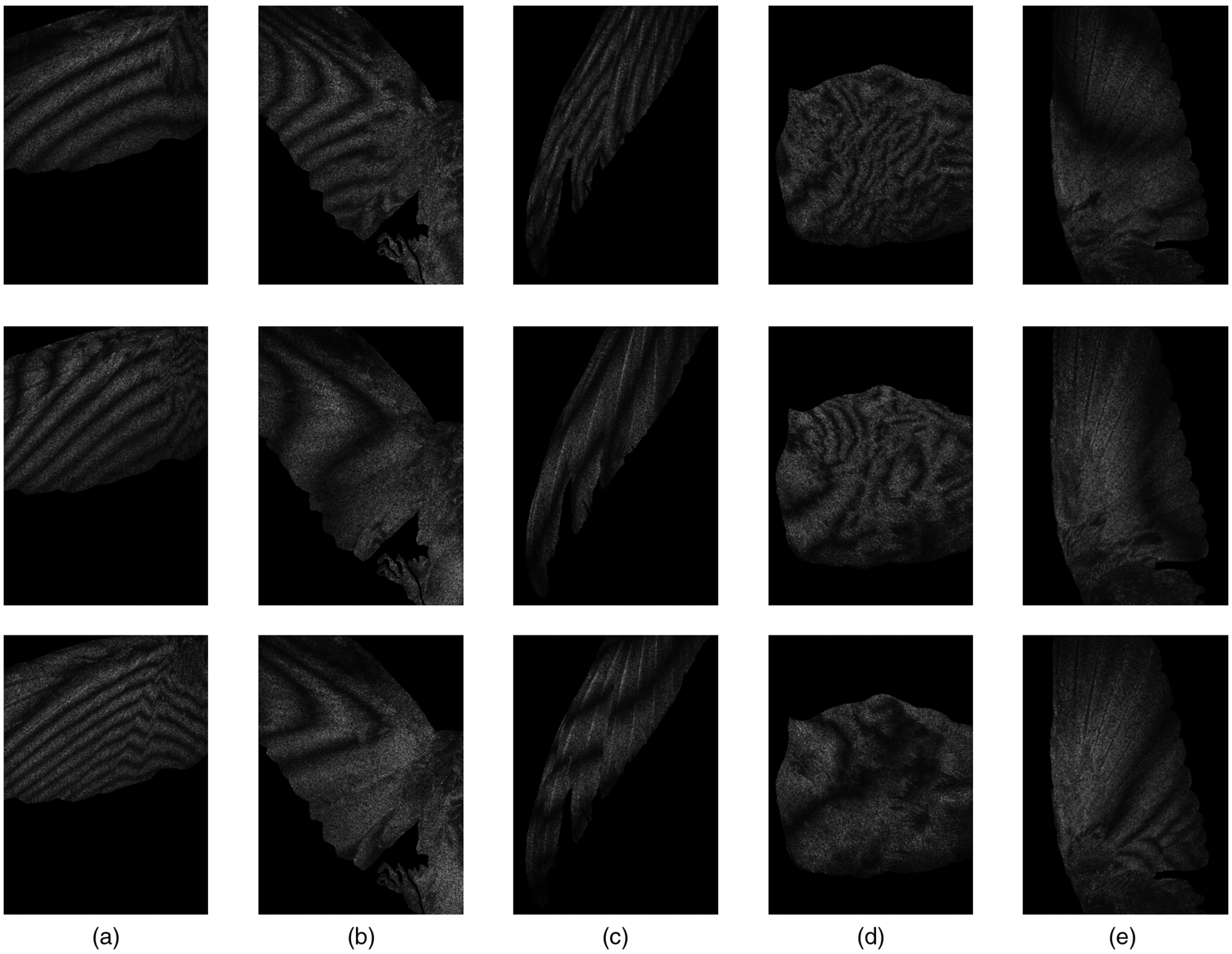

Fig. 5 Fringe patterns obtained from the hummingbird body sections of Fig. 4 at different instants, (5a1, 5a2 and 5a3) are from Fig. 4(a), (5b1, 5b2 and 5b3) are from Fig. 4(b), (5c1, 5c2 and 5c3) are from Fig. 4(c), (5d1, 5d2 and 5d3) are from Fig. 4(d) and (5e1, 5e2 and 5e3) are from Fig. 4(e).

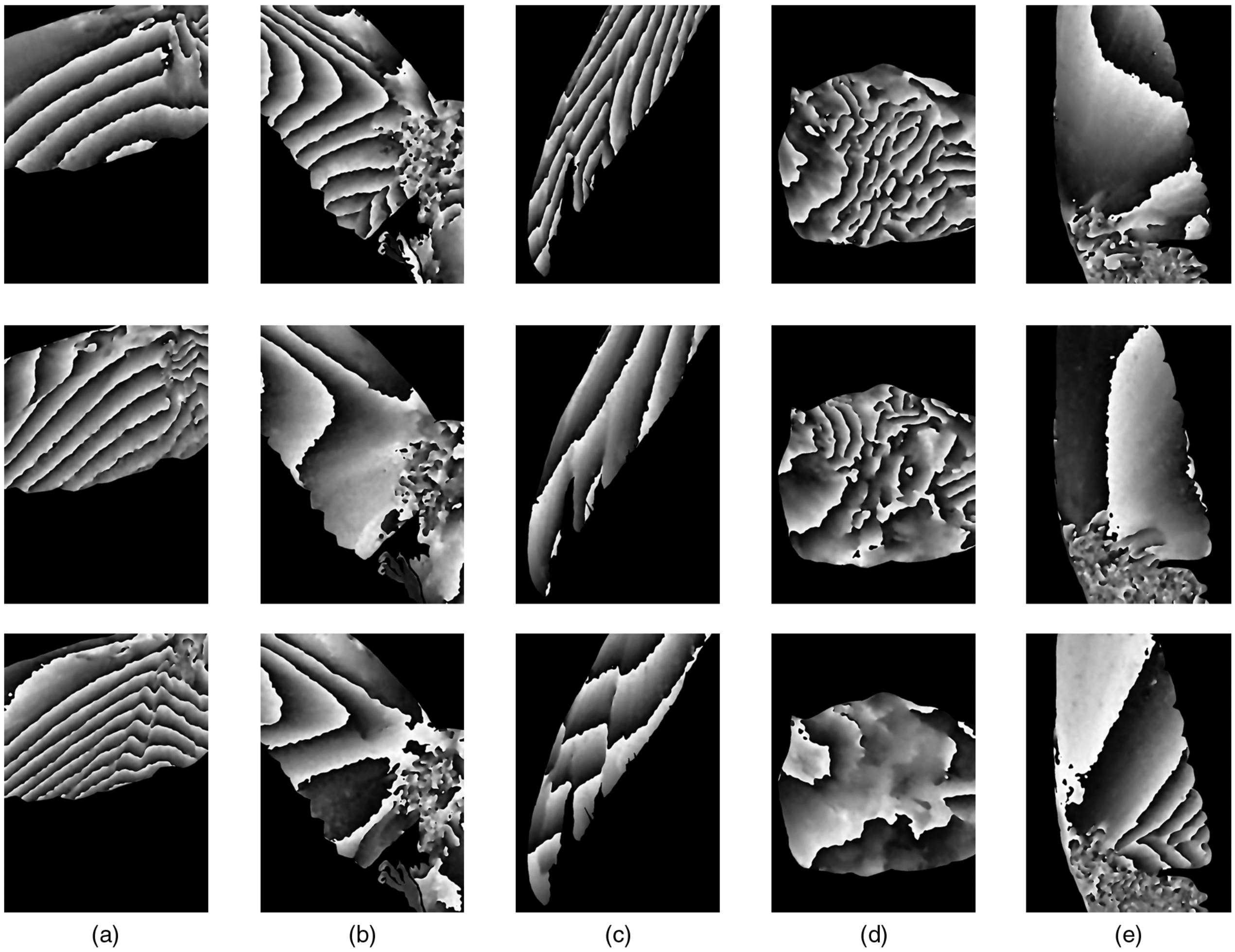

Fig. 6 Wrapped phase maps of the hummingbird's fringe patterns of Fig. 5.

in mind in order to keep the same illumination angle over all the bird's feathers during the tests.

3 Experimental Setup

A basic schematic view of the experimental setup is presented in Fig. 3, where the beam from a Verdi laser at 532 nm is divided into the reference beam (RB) and the object beam (OB) using an 80∶20 nonpolarizing beam splitter (BS). The selection of this BS helps to bring most of the laser beam onto the sample's surface with an illumination angle of 20 deg. Most of the backscattered light from the bird's feathers is collected and focused as an image into the interferometer by means of a lens (L) of 50-mm focal length with a circular aperture (A) in front of it. A high quantum efficiency charge-coupled device (CCD) camera with 1024×1280 pixels at 12 bits is used to record the reference and the OB interference pattern. This is made possible using a 50∶50

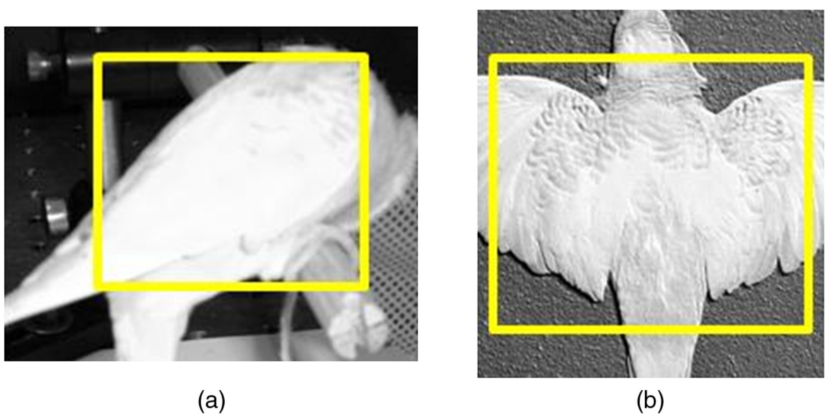

Fig. 7 Budgerigar body sections observed with the high speed system, (a) lateral and (b) dorsal view (during the tests, a mask is used in its head to avoid any eye damage from the laser).

beam combiner (BC) in front of the CCD camera. Under this configuration the field of view (FOV) of the system is 67×90 mm.

The hummingbird, *Cynanthus latirostrisis*, is quite a common specimen in this region of Mexico and may be found without a problem during several months of the year, giving us enough opportunities to safely and harmlessly capture and study one of them. The specimen captured for the experiment is a female of the species, easy to recognize due its bright colors. However, this type of bird requires very fast tests since it cannot be still for long periods of time, and hence no special preparation was used over the feathers. Taking extreme care, the hummingbird is held to a black nonreflective rubber block using rubber bands. This avoids any possible damage to the hummingbird and allows us to have it fixed during the required (very short) period of time needed to conduct the experiment.

Several different sections of the bird's body were illuminated in order to observe the interferometric response of the feathers. Figure 4 shows five different sections illuminated and analyzed by the DHI system that has a shutter to avoid any unnecessary laser illumination on the bird. A series of consecutive images were recorded for each one when any apparent movement of the bird was observed. The image capture procedure takes only a few seconds. There is not an external perturbation during the recording process to obtain the natural response of the feathers' backscattering light.

It is possible to obtain the fringe patterns by processing the image series obtained for each section in Fig. 4. These fringe patterns are the result of the feathers' natural movements during the test. Figure 5 depicts for each image (a–e) of Fig. 4, three fringe patterns from any three different instants during the test. It is readily seen the remarkable displacement variations in one single section of the bird due to the feathers' movement.

From Fig. 5 it is possible to observe that the number of fringes vary from section to section and even in the same image (fringe contour and inclination). This difference can

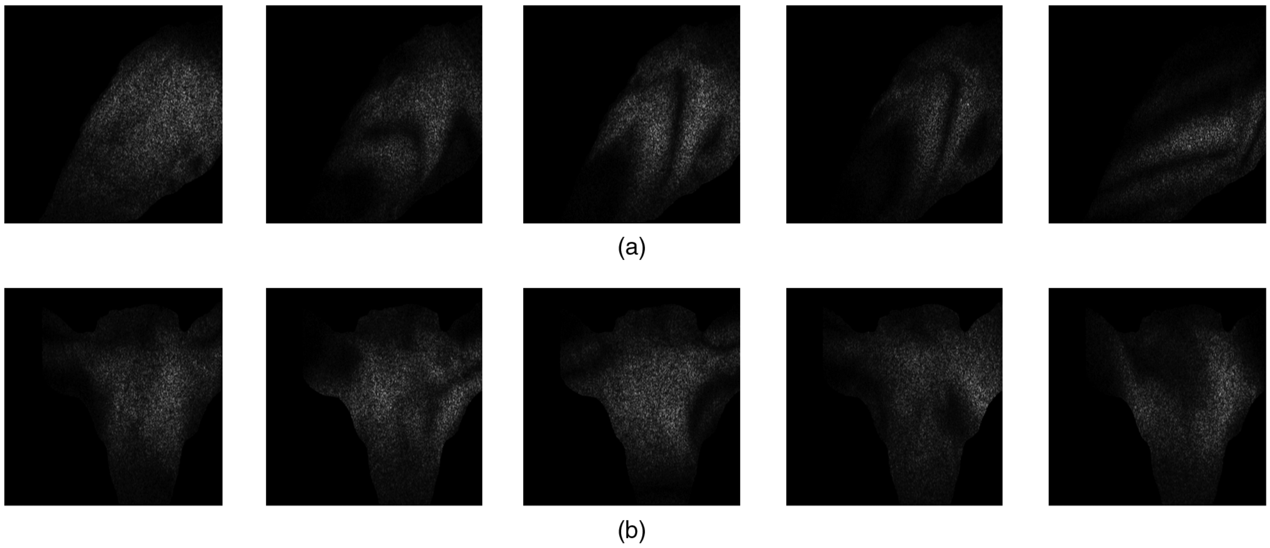

Fig. 8 Fringe patterns obtained at several time instants from the budgerigar (a1 to a5) and (b1 to b5) correspond to highlighted sections of Fig. 7(a) and 7(b), respectively.

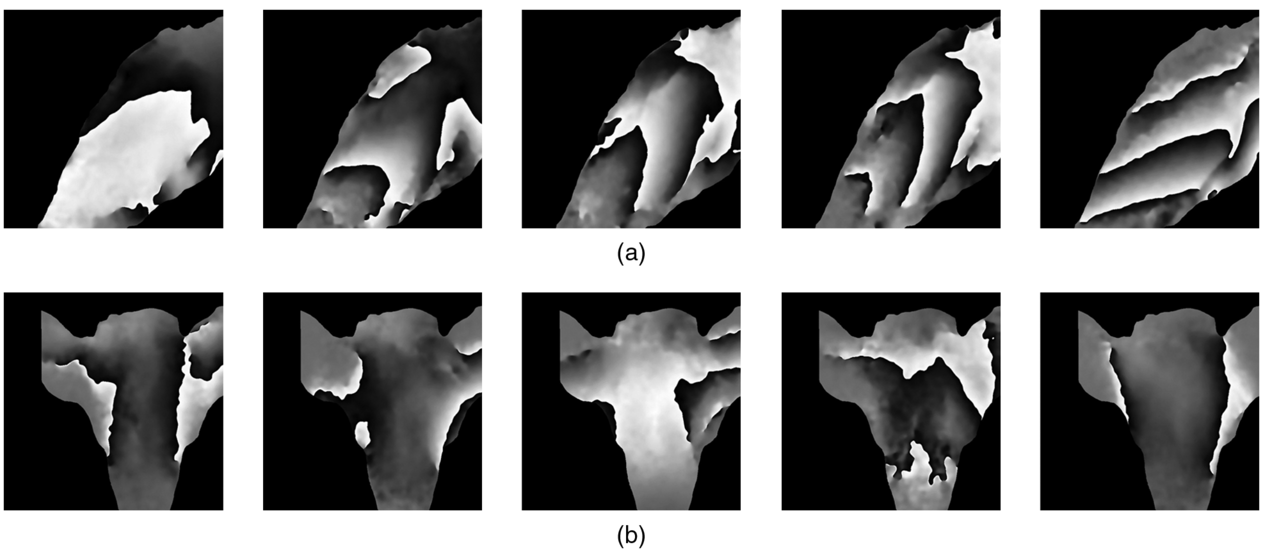

Fig. 9 Wrapped phase maps obtained from fringe patterns of Fig. 8.

have two possible explanations, one being due to the type of feather in that area, while the other is directly related to the displacement magnitude differences. As was mentioned before, there is an alignment in the feathers which diffracts coherent light in a direction where the interferometer does not recover it.

It is important to point out at this stage that a continuous displacement tracking or a full field measurement is not possible when looking at the wrapped phase maps of Fig. 6. To solve the temporal tracking, a re-referencing algorithm is used to recover the optical phase between consecutives images. The full field measurement can be achieved dividing the image in several masks corresponding to the same fringe pattern.

Even when some sections of these wrapped phase maps are smooth and suitable to be unwrapped, it is notorious that not all the images have the same condition. At this stage it is not possible to know which experimental parameter is affecting the speckle pattern which appears to be decorrelated in some particular areas. But one possibility is that the bird's movement is faster than the exposure time of the camera so blurring is introduced. Then, to prove this, a second test is performed using a high speed camera (1024×1280 pixels at 10 bits) recording at 5000 fps to observe a budgerigar (parakeet: *Melopsittacus undulatus*). This bird is easy to find in any pet shop, and more importantly, they do not present the same stress as the humming bird during the tests. Actually, the tests with the budgerigar were performed with the bird able to freely move, which required a change in the optical system FOV to 90×112 mm, by using a different focal length lens to cover the entire high speed camera sensor. The aim of this test is to observe a larger section of the bird where several feather types are found, and additionally, where the high speed recording will freeze any physical movement of the bird. Two different sections of the budgerigar are studied with this interferometer setup (Fig. 7).

Once the parakeet is in place, a series of images are recorded and processed in order to obtain the fringe pattern along the bird's body surface. In Fig. 8 it is possible to observe five different fringe patterns for each section of Fig. 7.

It is important to observe that clear fringes appear in consecutives images with a difference of 200 μs between them, which indicates the presence of a fast movement. A tailor-made algorithm gives the wrapped phase maps presented in Fig. 9. From these images it is possible to observe that there are still some regions where the optical phase is decorrelated.

At this point, low and high speed measurements were performed and in both cases certain areas of the birds' feathers present decorrelation. In those areas, the optical phase cannot be retrieved and hence no measurement is possible. To understand this, let's consider the following: each black and white fringe has an optical phase of 2π, which can be used in Eq. 2 to obtain its corresponding displacement. However, there is a maximum number of fringes that the system can resolve. As an example, an angle of 30 deg with 30 fringes (15 black and 15 white) gives a displacement of about 4.3 μm in a time lapse of 200 μs for the parakeet. Now, assuming that the bird may present a relative slow feather movement of 0.5 km/hr, we have a displacement of 27.7 μm for the same 200 μs.

As may be noticed, the number of fringes needed to capture such a speed are beyond the detection range of this interferometric system. However, the feathers' movement is not constant in all of them, i.e., some can move faster while others slower. For this reason it is possible to observe in the wrapped phase maps regions correlated and decorrelated. Besides, the layered arrange

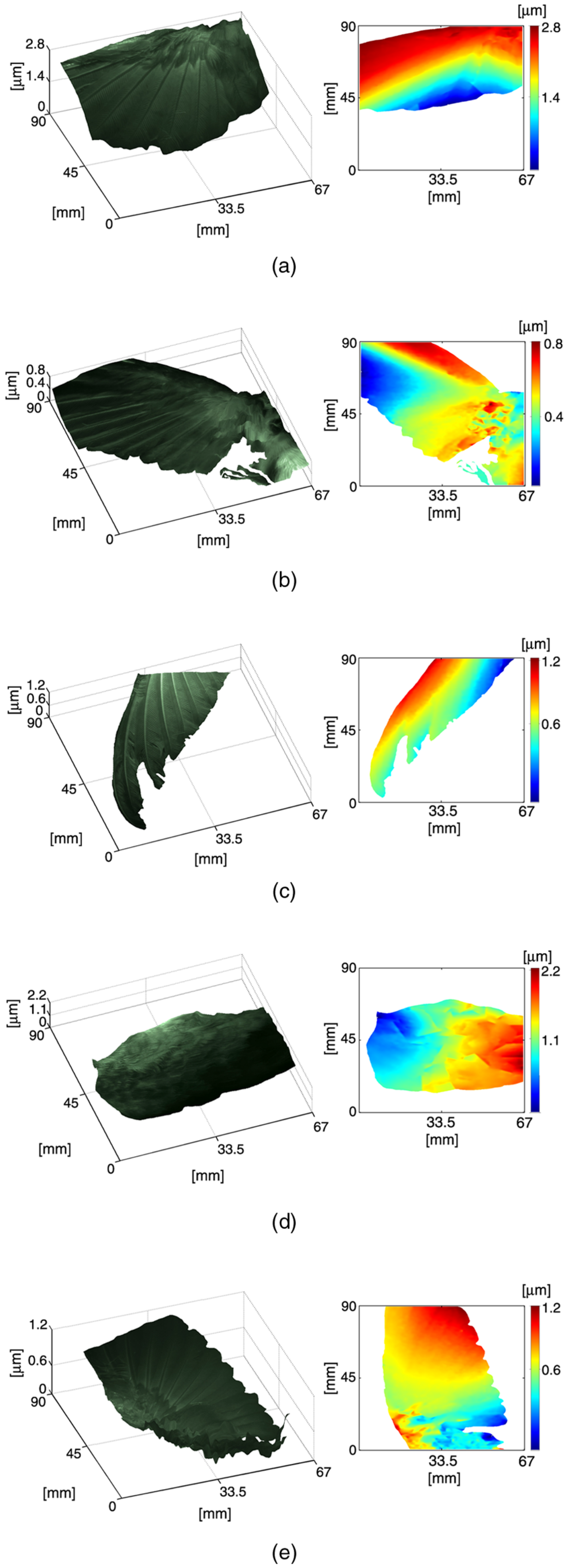

Fig. 10 Displacement maps obtained from the wrapped phase of (a) Fig. 6(a3), (b) Fig. 6(b2), (c) Fig. 6(c2), (d) Fig. 6(d2), and (e) Fig. 6(e1).

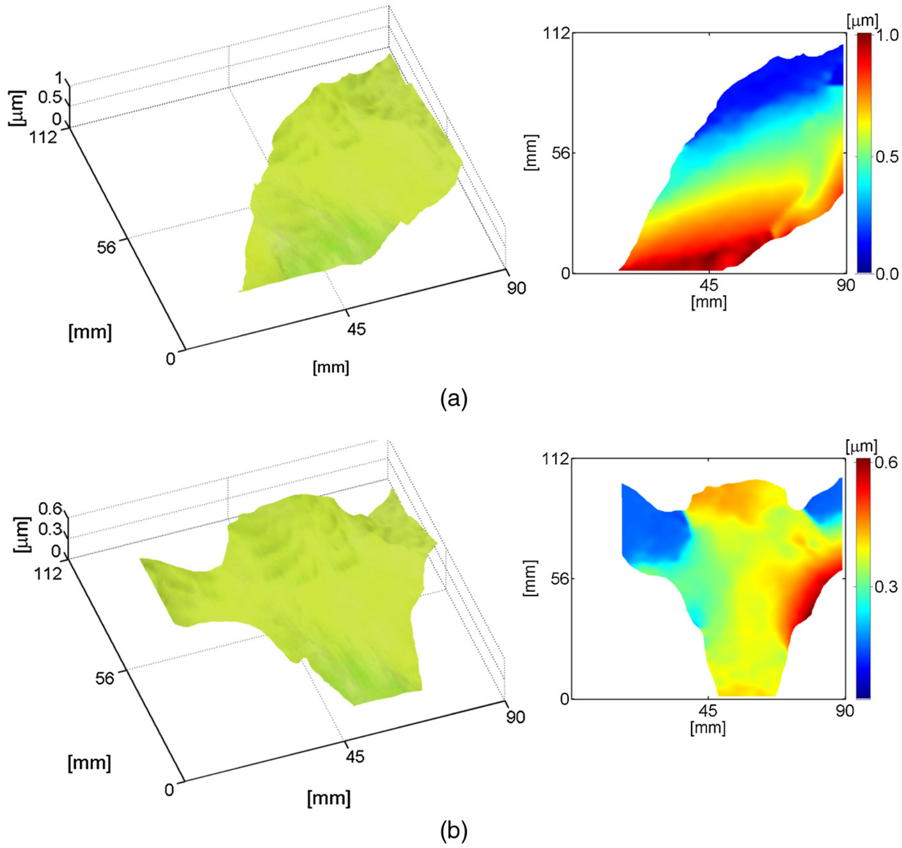

Fig. 11 Displacement maps obtained from the wrapped phase of (a) Fig. 9(a5) and (b) Fig. 9(b2).

of the feathers works as a diffractive object with a backscattering which is not always possible to recover by the interferometric system. This fast movement may be originated by the orientation of the barbs and how they affect the properties of the scattered laser light. It is possible to see that the optical phase can be easily affected by the feathers' movement and type when no preparation of the surface is made. However, even when an absolute long time tracking is not possible due to the decorrelation issue, the option of the continuous re-referencing process gives the relative displacement data which can be used to analyze which sections (feathers) suffer bigger displacements (movements).

Figures 10 and 11 show seven displacement maps resulting from each section shown in Figs. 4 and 7, respectively. All these displacement maps keep the same aspect ratio of their fringe pattern and wrapped phase map presented for each bird. The magnitude of these displacements is the resulting relative difference between two consecutives images. The way they are presented includes a new rendering algorithm which adds the real feather texture with a new concept for the measuring technique being used. This rendering is possibly due to white light data information taken simultaneously when the tests for each section were performed. Every rendered image includes an inset with a 2-D displacement image with a color bar for magnitude reference purposes. Figures 10 and 11 represent a 2-D mesh grid that includes the mask and the relative (re-referencing) algorithm. The latter avoids the signal decorrelation taking only consecutive images during the whole test. The mask avoids the 3-D representation with a regular mesh grid which gives a synthetic texture to the tissue. The rendering texture color represents the bird's feathers real color.

From Figs. 10 and 11 it is possible to observe different displacement magnitudes with a complex distribution pattern within one single image. This complexity is less notorious in Fig. 11 due to the slow movement introduced by the parakeet, while the humming bird shows a faster movement creating a high number of de-correlated clusters along its feathers' surfaces.

4 Conclusions

It was demonstrated that the proposed interferometric technique can obtain displacement measurements over complex organic samples with reasonable accuracy. The latter was probed in entire sections of two different kinds of bird where no special preparation was needed. Different feather types affect in different ways the speckle produced by the backscattering light, even when small areas of the bird are observed. It was found that this signal reduction is due to the feathers' movement and their alignment with respect to the interferometer. A particular problem found was that a live bird presents a fast feather motion which cannot be completely observed even at 5000 fps. This fast feather movement induced by the barbs and barbules gives a complex motion behavior among the feathers. A long observation distance helped to diminish the lost of signal in the interferometer as it can be observed near the edges of the budgerigar body where the roundness of its body changes the feathers' angle. The present research and results obtained may bring a new insight into biological research on this topic, giving new information about the superficial microdisplacement on a bird's body. Displacement maps can be successfully generated using advanced computing algorithms which split and process information for several regions among the feathers. We believe that this research work may open new doors for research in different disciplines, such as biology, physiology, aeronautics, etc., where complex biomechanic studies are required from otherwise difficult to prepare specimens, or indeed from specimens that will not show repeatable behaviors or have to be studied in a rapid test procedure.

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