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Holographic interferometry through imaging fibers using CW and pulsed lasers

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Abstract

The use of fiberoptic imaging structures for holographic investigations of displacement and vibration is demonstrated. Image-plane holograms are formed at the proximal output end of an imaging multifiber. Investigations using a cw laser for double-exposed holograms of a cantilever beam, as well as time-average vibration studies, were conducted. Pairs of double-pulsed holograms of dynamic events were recorded, one through the fiber bundle, the other in a conventional manner as a standard of reference. The fringes of both holograms were practically identical.

The ability to perform measurements in holographic interferometry through optical fibers should lead to further developments in medical endoscopy as well as industrial applications.

Introduction

The use of optical fibers in holography has many advantages, in particular for investigations of obscured or remote objects in difficult environments. Holographic endoscopy (endoholography) provides the advantages of intracavity imaging with high resolution and large depth of field in three dimensions.

Endoholography can be divided into two categories:

1. Recording of an intracavity, high resolution 3-D image.
2. Intracavity, noncontact vibration and deformation measurement using holographic interferometry techniques with 2 or 3 dimensional imaging.

The first presentation of a holographic endoscope was made by Hadbawnik[1] in 1976, stressing the three-dimensionality and large depth of field advantages.

In a standard endoscope a flexible aligned imaging multimode fiber bundle or multifiber is often used. Imaging through such a bundle using holography has no advantage over conventional photography since the 3-D effect is lost and the resolution is limited to the resolution of the multifiber which is still rather low ($\sim$50 line pairs/mm). However, in the case of holographic interferometry the imaging multifiber allows for the external recording of a hologram, which means that a standard endoscope, equipped with laser light illumination, can be used.

The first investigation of using an imaging multifiber for holographic interferometric time-average vibration studies was presented by Uyemura et.al.[2] in 1979. The diaphragm of an earphone was illuminated through a fiber bundle from a cw laser. The image was transmitted through another fiber bundle . The hologram was recorded at the output end where a reference beam was added without using a fiber. The same year Grünewald et.al.[3] reported a study using a commercial endoscope to record deformations from the inside of a GFRP tank with double-exposed holograms with a cw laser. The purpose of the investigation was to show the feasibility of endoscopic-holographic interferometry, in particular in urology, where in-vitro bladder deformations were studied, showing the possibility of detecting early lesions.[4]

For in-vivo investigations in medicine as well as in many industrial applications, it is essential to utilize a pulsed laser. von Bally[5] used an artifical tympanic membrane illuminated by a double-pulsed ruby laser through a standard endoscope fiber bundle for object illumination only. The holograms were recorded using a thermoplastic camera. Yonemura et.al.[6] investigated the fringe visibility obtained using imaging multifibers and a cw laser for endoscopic-holographic interferometry. They also showed the feasibility of using a pulsed laser. Gilbert and Herrick[7] and Gilbert et.al.[8] investigated also the possibilities of using a multimode fiber bundle for hologram interferometry and cw lasers.

The first use of a single-mode fiber for transmitting a reference beam from a Q-switched ruby laser was presented in 1982 by von Bally[9] in an investigation of an artifical tympanic membrane. In 1982, an in-vivo holographic recording of vocal cords from an anesthetized dog was published by Raviv et.al.[10], using a Q-switched ruby laser. The object light was

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transmitted through a multimode fiber and the reference beam through an articulated arm. Single-exposed reflection holograms were recorded of the oropharynx and vocal cords showing details which could not be observed by indirect laryngoscopy.

Dudderar and Gilbert[11] showed that a pulsed ruby laser could be used for single exposures using multimode optical fibers to suppress the ambient motion related instabilities associated with the application of these imaging fiber bundles. On the other hand, in the work described in this paper, both the object and reference light were guided through multimode fibers as well as the image was transmitted through an aligned multifiber.

Rowley[12] used a fiber-optic bundle for the reference beam to produce image-plane interferometric holograms using a cw laser. Double-exposed holograms were made of a pressurized cylinder, which could be reconstructed by means of a broadband extended source.

A real-time holographic interferometry system utilizing single-mode fibers both for object and reference beams in combination with a recording B.S.O. crystal and classical four-wave mixing was presented by Herriau et.al.[13]

The possibility of transmitting not only the image through a fiber bundle but actually the hologram itself (i.e. the interference fringes constituting the hologram is generated at the input end of the fiber bundle and recorded at the output end) was demonstrated by Dudderar et.al.[14] If the spatial frequency due to the angle between the object and reference beam is low and not exceeding the resolution limit of the bundle it is possible to transmit an Ultra-Low Frequency hologram. The application of ULF-holograms for holographic interferometry measurements was presented by Gilbert et.al.[15]

Gilbert et.al.[16] have stressed the advantages of using single-mode fibers for holographic interferometry and thereby reduce the stability requirements within the holographic set-up.

Albe[17] has used single-mode fibers combined with a pulsed laser for possible high-speed holographic recordings.

The application of a gradient index rod lens for endoscopy where the same GRIN element is used for both object light illumination and image transmittance has been reported by von Bally et.al.[18,23] The main advantage, in this case, is that the combined utilization of a large diameter single optical element, filling the entire available and usually limited space in an endoscope, has the advantage of reducing the speckles, which will be larger if two different, smaller diameter fibers were used separately for object illumination and image transmission.

A holocamera with single-mode fiber illuminators and an image fiber bundle for real-time remote measurements of surface displacements and deformations has been developed by Dudderar and Gilbert.[19]

Special considerations concerning coupling of pulsed lasers to single-mode fibers for holographic applications have been described by Bjelkhagen.[20]

The development of a special fiber structure for endoholography has been described by Raviv et.al.[21] with a pulsed holographic application presented by Marhic et.al.[22]

The present investigation is a study of the use of aligned imaging multifibers in endoscopic-holographic interferometry, mainly in combination with a Q-switched pulsed laser for possible medical in-vivo investigations as well as dynamic, industrial applications. A pulsed laser is essential for all these types of investigations. However, movements of the multifibers that eventually occur between pulses can cause problems in a practical situation. The main emphasis in the investigation was to study this problem.

Theory

A theoretical explanation of the ability of imaging multifibers to preserve interference fringes has been presented.[6] It is based upon a ray analysis which assumes a single path length through each fiber, and hence appears to be limited to single-mode fibers. Here we present a field description which is valid for multimode fibers.

Consider the arrangement in Figure 1. Lens L_1 produces an image of the object O onto the input face of FB. This results in another image in the output plane of FB, itself imaged by L_2 onto H. In the rest of this section we assume that the temporal coherence of the source and path differences are such that interference can always be achieved. Hence we assume a model in which the source is strictly monochromatic, with angular frequency w. Then all fields in the system can be studied by omitting the common time dependence $e^{i\omega t}$, and by dealing only with complex vectors which are functions of space only.

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Electromagnetic propagation theory indicates that in order to know the field distribution $\vec{b}\,(x_\iota, y_\iota)$ in some output plane of a system, one needs to know the input field distribution $\vec{a}\,(x_o, y_o)$ in some reference plane, and the linear operator which relates the two via

$$\vec{b} = \mathcal{L}\,[\,\vec{a}\,] \tag{1}$$

Concerning the optical system L_1 - FB - L_2, the output plane of interest is H. The input reference plane, R, is the image of the input face of FB through L_1, i.e. nominally coincident with O (it is convenient to think of R as being slightly in front of O). L_1 and L_2 are assumed to be ideal lenses, with impulse responses which are essentially δ-functions. The operator $\mathcal{L}$, representing propagation from R to H, is thus basically determined by the properties of FB: This structure, made of multiple discrete multimode fibers, is spatially variant when studied with high resolution; when examined with low resolution, however, it exhibits the usual imaging properties.

Regardless of the exact nature of $\mathcal{L}$, its basic linearity still allows us to write that if ϕc is a constant over R,

$$\mathcal{L}\,[\,e^{\iota\phi c}\;\vec{a}\,] = e^{\iota\phi c}\,\mathcal{L}[\vec{a}] = e^{\iota\phi c}\,\vec{b} \tag{2}$$

Hence, if the entire input to the system is phase-shifted by a uniform phase ϕc, then so is the output.

Consider now the situation of interest where O in 1 (2) produces a field $\vec{a}_1$ ($\vec{a}_2$) in R and $\vec{b}_1$ ($\vec{b}_2$) in H. Let us assume that the displacement (or deformation) between 1 and 2 corresponds mainly to displacements along the normal. In that case, we can write that[24]

$$\vec{a}_2 = e^{\iota\phi\,(x_o,\, y_o)}\,\vec{a}_1, \tag{3}$$

where $\phi\,(x_o, y_o)$ is a possibly non-uniform phase shift. According to Eq. (1), we then have

$$\vec{b}_2 = \mathcal{L}\,[\,\vec{a}_2\,] = \mathcal{L}\,[\,e^{\iota\phi(x_o,\, y_o)}\,\vec{a}_1\,]. \tag{4}$$

When $\phi\,(x_o, y_o)$ is non-uniform, we cannot in general proceed as in Eq. (2). However, if the phase shift resulting from $\phi\,(x_o, y_o)$ at the input face of FB varies very little across each fiber input, then that phase shift will be transmitted uniformly through each fiber (similarly to Eq. (2)). Under those circumstances, Eq. (4) becomes

$$\vec{b}_2 = \mathcal{L}\,[\,e^{\iota\phi(x_o, y_o)}\,\vec{a}_1\,] = e^{\iota\phi(x_\iota, y_\iota)}\,\mathcal{L}[\vec{a}_1] = e^{\iota\phi(x_\iota, y_\iota)}\,\vec{b}_1$$

(unit magnification and appropriate choice of the origins of coordinates are assumed).

Hence, when a slowly-varying phase shift modulates the input of the system, it also modulates the output. It is now clear that recording of both $\vec{b}_1$ and $\vec{b}_2$ on the same hologram will lead to the display of interference fringes in the hologram plane, which are the same as would be observed by taking a double-exposed hologram of the object itself.

Investigations using a cw laser

Initally, experiments were performed with a He-Ne laser and an aligned imaging multifiber made by American Cystoscope Makers (length 72", bundle diameter 5 mm, fiber diameter 10 µm). The purpose of these studies was mainly to verify the results obtained in earlier investigations, and, in particular, to study the stability problem associated with multimode imaging multifibers.

Double-exposed holograms of a cantilever beam were made as well as time-average holograms of a loudspeaker, using the imaging multifiber only. Object and reference illumination were arranged using conventional optics. Image-plane holograms were recorded externally by means of a positive lens between the output end of the imaging multifiber and the holographic plate. A lens was used to image a portion of the object at the input end of the multifiber, while a similar lens at the output end imaged the output of the multifiber onto the holoplate for an image-plane hologram. The advantage of this type of hologram is that it can be reconstructed with white light, and hence no speckles. Good results were obtained for both test objects when the multifiber was supported in a stable manner.

The multimode imaging multifiber works very well for cw holography as long as the fiber is stable. Small movements of the multifiber can actually occur without completely destroying the recordings. This is very important for double-pulsed in-vivo endoscopic investigations, as small bundle movements will occur during the interval between the pulses. For the cw application these movements were studied in reference 6, where a 300 µm movement of the fiber was found acceptable without considerable effect on the interference fringes.

Investigations using a pulsed laser

Our main interest was to study in more detail the behavior of the imaging multifiber in conjunction with a pulsed laser system. A 1-Joule, double-pulsed ruby laser, made by JK-Lasers (System 2000 HLS 2), was used in two different arrangements. In the first experiment the object light was arranged in a conventional way using a negative lens. The fiber bundle from ACMI was used here in the same manner as for the cw laser experiments, Figure 2. The main purpose here was to study only the properties of the fiber bundle itself. A loudspeaker was used as the test object, and double-pulsed holograms were taken with different pulse separations.

In the second set up, the object was illuminated through a fiber, which simulates the manner in which a real endoscopic investigation will be performed, Figure 3. Vibration patterns from the loudspeaker were recorded. A conventional transmission hologram was recorded very close to the input end of the imaging multifiber for comparison to the image-plane hologram recorded simultaneously at the output end. The reference for the image-plane hologram was arranged using conventional optics, since, in an endoscopic application, this part will always be recorded externally.

The following experiments were performed:

1. Double exposures (with two single pulses) of the vibrating loudspeaker membrane with a long delay (> 30 s) between the two pulses and a stable fiber bundle.

2. Double exposures (with two single pulses) of the vibrating loudspeaker membrane with a long delay (> 30 s) between the two pulses, where the middle of the imaging multifiber was moved $\sim$10 cm between exposures.

3. Double exposures (with normal double-pulse operation of the laser) of the vibrating loudspeaker membrane with a delay of 200 μs between the two pulses and an unsupported, loose bundle which was not purposely moved between exposures.

4. Double exposures (with normal double-pulse operation of the laser) of the vibrating loudspeaker membrane with a delay of 200 μs between the two pulses, where the bundle was vibrating with movements not exceeding expected fiber movements during real in-vivo endoscopy.

The results of these investigations are shown in Figures 4-9. The photographs of the image-plane holograms have been recorded using a filtered white light reconstruction technique. The image-plane holograms are placed side by side with the simultaneously recorded conventional holograms showing the same area of the membrane. The agreement between the two types of holograms is good. No difference was found if a fiber object illumination was used instead of conventional optics.

In Figure 4 is an example of holograms recorded with a long delay (> 30 s) between two single pulses and a stable multifiber, while Figure 5 shows the same pulse separation and a large movement of the bundle between exposures. In this case the fringe pattern is completely lost in the image-plane hologram. Figures 6-8 show smaller and smaller fringes in double-pulsed holograms (Δ = 200 μs) of various amplitudes. The resolution limit of the multifiber is reached in Figure 8, where the closely spaced interference fringes are almost not resolved in the image-plane hologram. Figure 9 shows an example from the test of a hand-shaken multifiber with short pulse delay, and there is good fringe pattern correlation between the two holograms in spite of the jiggling image carrier.

A final experiment was performed with a bioprosthetic aortic heart valve as the test object. A lower fringe contrast was observed in this case. The reason is the penetration of the red laser light into the tissue. This was also reported as a problem faced in the urinary bladder investigation, where the bladder had to be powdered to obtain good contrast.[4] However, acceptable contrast has been obtained from untreated human skin in several investigations, e.g., chest motion studies.[25]

The improved fringe contrast that can be obtained using green laser light indicates that a frequency-doubled Nd-YAG laser will be more suitable to utilize than a ruby laser for medical applications of endoscopic-holographic interferometry.

Conclusions

Endoscopy is a continuously expanding modality in diagnosis and therapy. It provides convenient means of exploring and treating internal organs and tissue without the need for incisions. The applications of holographic interferometry have, so far, been limited

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to external and, thus, accessible parts of the body. The use of holographic interferometry in endoscopic procedures should greatly enhance its diagnostic potential; e.g., the measurement of compliance of the walls of the bladder or of arteries may provide significant diagnostic indicators of early stages of disease.

The endoscopic application of holographic interferometry, as described in this paper, allows for the use of existing endoscopes. Hence, the development of new diagnostic procedures, which utilize holographic interferometry, should be facilitated by already existing endoscopic instrumentation and techniques.

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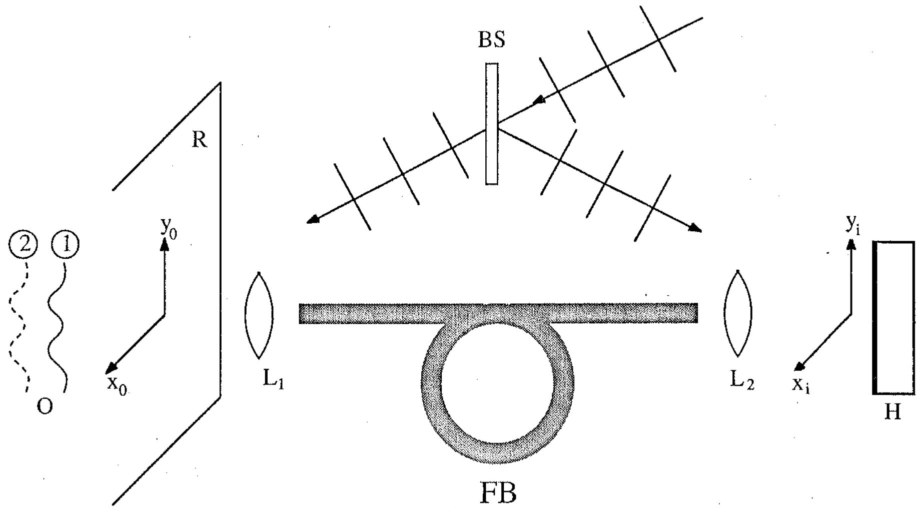

Figure 1. Schematic for the theory of holographic recording of images transmitted through the fiber bundle FB; H = holographic plate.

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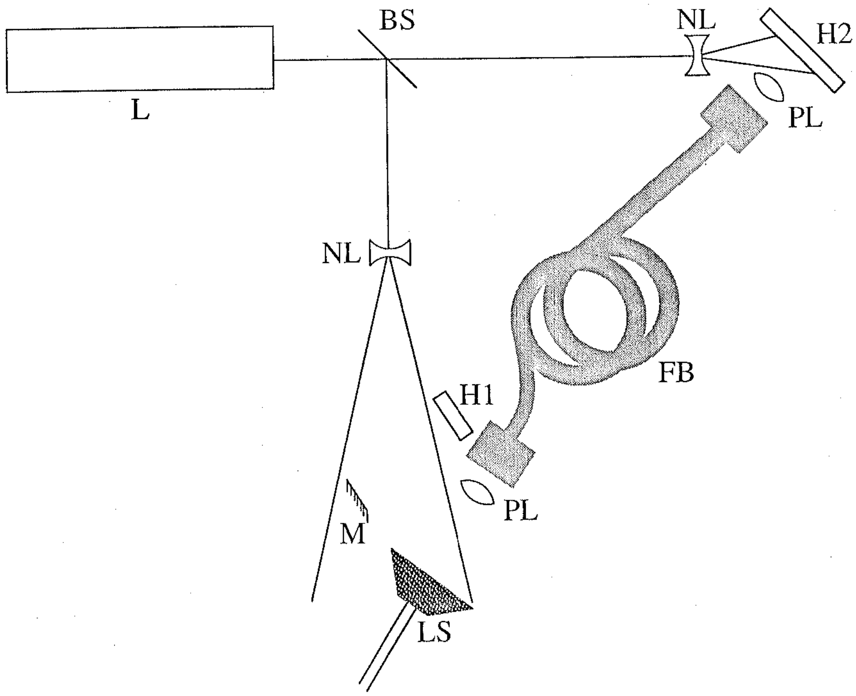

Figure 2. Set up with imaging multifiber and conventional object illumination. H1, reference hologram. H2, image-plane hologram.

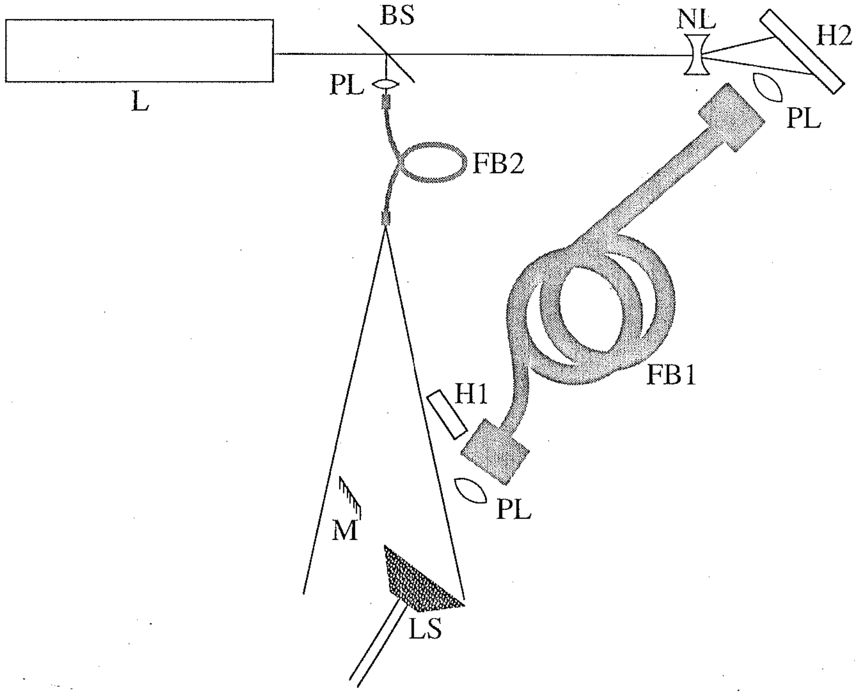

Figure 3. Set up with imaging multifiber and fiber object illumination. H1, reference hologram. H2, image-plane hologram.