Measuring full displacement fields on scattering surfaces by a portable low-cost interferometer

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Abstract: - The paper presents a device for measuring full displacement fields working on the principle of speckle interferometry. The proposed interferometer was designed with the aim of obtaining a lightweight self-contained device, easy to assemble with cheap and standard equipment. The investigated area is illuminated by three laser diodes emitting 50 *mW* at 660 *nm*, and observed by a B&W firewire CCD camera. The accuracy of the measurements is improved by means of a PZT actuator realized on purpose and driven by a control electronics able to provide a very accurate supply voltage. Furthermore by the control electronics it is possible to turn on and off the diodes and to control the single light intensity of each laser. The paper describes in details all the parts of the interferometer and the systems implemented for optimizing the working conditions of the device. Furthermore all the steps necessary for performing the measurements are reported, and typical sets of experimental data are shown.

Key-Words: speckle interferometry, laser diode, phase-shifting, low-cost, 3D deformation, portable equipment

1 Introduction

Speckle interferometric techniques, assessed in the late 60's and first 70's, are nowadays powerful means for carrying out non-contact full-field measurements with high accuracy [1-3].

beginning this new At the family of interferometric techniques represented the natural evolution of the holographic techniques [4-5], basically due to their capability to be implemented without the expensive and time-consuming chemical processing of the holographic plates. However speckle techniques were still suitable for laboratory experiments only, due to the high cost of many equipments (i.e. coherent light sources, optical sensors) and the high sensitivity to the mechanical environmental background (i.e. vibrations, thermal gradients). Furthermore in the succeeding years the introduction of the phaseshifting procedures [6] introduced new expensive components (i.e. piezoelectric actuator).

Over the years, after speckle interferometry had become a well-assessed experimental technique, many researchers focused their efforts in order to obtain cheaper and lightweight devices, able to work properly also far from the anti-seismic bench and out of the controlled environment of the laboratory. The parts whose weight and cost were strongly reduced over the years are the light sources and the piezoelectric actuators.

The most popular high coherence light sources for interferometric applications, after the laser invention in the 1958 [7], are based mainly on He-Ne and Ar-Ion technology. The first type is normally characterized by a low output power (<50 mW), while the second type by a very high power absorption (several kW) which normally requires proper cooling systems. Anyway both types are cumbersome and expensive devices.

In the last years new types of light sources are diffusing for scientific applications, the laser diodes and the pumped diode lasers. The laser diodes [8-9] are very compact devices and normally are available on the market in two geometrical versions, 5.6 mm and 9.0 mm packages. The single mode output power spans from few mW to 1 W and the wavelength from 400 nm to 1500 nm. In order to work properly the diode must be assembled into specific mounts and supplied with DC voltage controllers. These sources are very cheap, small and lightweight. Their drawbacks reside in the power and wavelength stability and in the mechanical weakness of the package.

The diode-pumped solid-state lasers (DPSSL) [10-11] are more expensive sources than the laser

diodes, but these are capable of providing high optical and mechanical stability and a very high temporal coherence. Moreover a very high output power can be attained (up to 20 W) against a reduced input absorption if compared with the Ar-Ion lasers, and many portable versions are available too.

The piezoelectric actuators are one the most phase-shifter popular type of used for interferometric applications [12]. The most important limitation for these devices is not the weight or the dimensions, but the cost; in fact, in order to ensure a very accurate control of the optical paths and due to the presence of non-linearity and hysteretic behavior, they are equipped with motion sensors and complex feedback control electronics, which obviously increase significantly the prices.

With the aim of disposing of a low-cost phaseshifter the researchers can follow essentially two approaches: adopting innovative hardware (mechanical and/or electrical) solutions [13-14], or implementing more or less complex software procedures able to predict accurately the electromechanical behavior of the actuator [15-17]. The literature regarding these topics is broad, as proved by the several articles published in journals and conference proceedings.

Finally, reducing as much as possible the most expensive elements, like retardation plates or optical fiber launcher, can further decrease the cost of the optical set-up.

At present some portable speckle interferometers or part of these are available on the market [18-19]. Moreover technological centers specialized in optical techniques able to provide their metrological expertise can be easily found on the web [20].

commercial devices implies Using the advantages of not being involved in the issues of the correct implementation of the measurement equipment (i.e. alignment, calibration. optimization), and, above all, the users do not need an expertise in optical techniques. On the other hand using a "plug-and-play" interferometer does not allow much flexibility, thus many adjustments cannot be performed because usually all the optical components of these devices are sealed into a closed case. Furthermore the software for managing the equipment, usually supplied by the seller with the hardware, provides only heavily processed output data; hence the image processing and the treatment of experimental data, which represent in speckle interferometry a critical stage of the measurement operations, cannot usually be controlled in detail.

The paper presents an interferometer designed and realized with the aim of obtaining a low-cost and portable device working on the principles of speckle interferometry. The device is equipped with laser diodes and a non-commercial three piezoelectric actuator. The lasers and the actuator are driven by a control electronics designed and realized on purpose. The interferograms are acquired by a Sony B&W CCD camera. All the operations are controlled by a personal computer (even a modern laptop of standard performance fits for the purpose) running in LabVIEW or MatLab environment and interfaced with the control electronics by a USB port, and with the CCD camera by a Fire-Wire port. The interferometer allows measuring three displacement components by which the whole 3D deformation field can be retrieved. All the steps necessary for correctly performing the measurement procedure are described in details, and the typical sets of experimental data are reported.

2 The experimental equipment

The experimental equipment is formed by two parts: the control electronics interfaced with a laptop and the interferometer.

The control electronics, assembled into a 19-inch rack module, provides 9 output ports; the front panel is reported in Fig.1. In particular the first 4 ports (DAC#1-DAC#4, BNC connectors) provide the supply voltage for the piezoelectric low-voltage ceramics, this voltage can be varied in the range [0-100] V with the resolution given by a 16 bit digitalto-analog converter. The second 4 ports (DAC#5-DAC#8, RCA connectors) provide the supply voltage for the laser diodes, in this case a 12 bit DAC is used for supplying a voltage in the range [0-3] V. Under each of these 4 ports a system formed by two plugs allows placing a resistor for controlling the current of the laser diodes. A final port (MOTORI, DIN connector) is available for driving two DC motors, but in the present work they will not be mentioned any longer.

In the rear panel of the control electronics, which is not reported in Fig.1, a serial port (RS-232) is present and it allows sending commands to set the voltage of each port via software by the laptop; the cable which connects the laptop to the control electronics, visible in Fig.1 on the top of the device, adapts the USB port of the laptop to the serial port RS-232 of the control electronics. The commands to the port can be sent by the standard routines for input-output operations available in the conventional software environment normally used for instrumentation control. i.e. National Instruments LabVIEW or MatWorks Matlab-Simulink.



Fig.1. The front panel of the control electronics interfaced with the laptop (not shown) and the adapter USB/RS-232 cable.

The interferometer is a lightweight compact device based on Michelson design; a picture of the whole assembly is reported in Fig.2. Three single mode laser diodes Hitachi model HL6512MG with an optical output power of 50 *mW* at 660 *nm* are used for illuminating the object along three non coincident directions. The diodes are mounted in the assembly formed by the collimation tube (Thorlabs, model LT220P-B) and the strain relief/electro-static discharge protection (Thorlabs, model SR9C).

The interferograms are acquired by a Sony CCD camera model XCD-X710 with a sensor of 1024x768 pixels (pixel size $4.65x4.65 mm^2$). The camera is interfaced with a laptop by the IEEE-1394 Fire-Wire port and it can operate either in interlaced or in progressive mode. The observation direction is vertical, according to the picture reported in Fig.2.



Fig.2. The assembled device.

The piezoelectric actuator for applying phaseshifting procedure is a non-commercial device designed, realized and calibrated on purpose by the authors [14]. It is obtained by assembling three PZT ceramics Phisik Instrumente model PL033.30 into an elastic stainless steel case. The electromechanical solution adopted for realizing the actuator allows obtaining a highly rectilinear stroke of about 1.7 μm .

The imaging is obtained by two achromatic doublets, mounted in the opposite way with respect to the propagation direction of the light. By mounting opposite each other the sides from/to which the parallel rays propagate, the image and the object planes are located at a distance equal to the focal lengths from the respective doublet. In this way the magnification ratio, equal to ratio between the focal lengths of the doublets, can be varied discontinuously by substituting the doublet in front of the object plane with another one of different focal length, and without modifying the distance between the sensor of the CCD camera and its respective doublet.

Figure 3 reports a partial section of the Michelson interferometer drawn from the 3D model used for designing the device. The two beams are obtained by a non-polarizing broadband cube beam-splitter. The object beam is sent to the CCD sensor by a mirror driven by the PZT actuator, while the reference beam is sent to the sensor by a second mirror mounted on a three degree-of-freedom platform (recognizable by the adjustment screws visible in Fig.2 and Fig.3), necessary for the correct alignment with the piezo-actuated mirror.



Fig.3. A 3D model of the Michelson interferometer.

The intensities of the reference and object beams, and thus their ratio, are adjusted by two rotating plates: a quarter-wave plate placed along the arm of

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the non-actuated mirror, and a polarizing plate placed between the beam-splitter and the doublet in front of the CCD camera. A further polarizer is placed at the entrance of the Michelson interferometer, in front of the doublet. It is not necessary if the laser is polarized and the observed surface does not depolarize the light, but these two conditions are not always fulfilled.

Figure 4 explains how the plates allow equalizing the two interfering beams. The object beam – Fig.4a) – hits only the two polarizers, thus the amplitude of outgoing object field u_{oo} can be evaluated as follows:

$$u_{oo} = u_{oi} \cos\beta, \qquad (1)$$

with u_{oi} object field outgoing from the first polarizer and β angle between the two axes of polarization (P_i and P_o).



Fig.4. Amplitude of the interfering fields: a) object beam; b) reference beam.

On the other hand the reference beam – Fig.4b) – hits the two polarizers and the quarter-wave plate. When polarized light gets through the quarter-wave plate two times, this acts like a half-wave plate and then rotates the polarization axis symmetrically with respect to the fast axis of the plate. Hence the amplitude of outgoing reference field u_{ro} can be evaluated as follows:

$$u_{ro} = u_{ri} \cos(\beta - 2\alpha), \qquad (2)$$

with u_{ri} reference field outgoing from the first polarizer, u_{ri}^{\prime} reference field outgoing from the quarter-wave plate and α angle between the axis of ingoing polarizer (P_i) and the fast axis of the retardation plate (F).

If eq.(1) is set equal to eq.(2) the solution of the equation yields the pairs (α , β) which satisfy the optimal condition of interference. Figure 5 provides a family of curves for evaluating the aforementioned pairs; these curves are parameterized by the ratio between the intensities of the ingoing object and reference beams, obtained by squaring the ratio of

the corresponding field amplitude, $(u_{oi}/u_{ri})^2$. The graph shows that for each intensity ratio two pairs exist which satisfy the condition of equal intensity for the two interfering beams.



Fig.5. Pairs (α , β) giving equal intensity of the object and reference beams for different incoming intensity ratios $(u_{oi}/u_{ri})^2$.

Apart from the first polarizer, all the optical elements are crossed by parallel rays, this fact implies a good working condition, minimizing the effect of aberrations.

The laser diodes and a diaphragm (for controlling the speckle dimension) are fixed on a module that can slide along four rods, in this way it is possible to illuminate the investigated area at different distance from the first doublet, and without modifying the angle of the illumination directions.

All these parts of the interferometer are assembled by using Linos components (Microbench series system): modular mechanical elements in anodized aluminum that allow realizing stiff and high precision optical setups. The whole equipment is contained in a volume of about 200x300x300 mm³, the weight is about 2 kg. The position of the device is defined by three extendable legs, two of which are moved by micrometers, whereas the third manually.

By the optical layout described above, the reference beam is obtained by imposing a slight misalignment of the mirror fixed to the three DOF platform. In this way the interference is obtained between the light scattered by two close surfaces placed not far from the observation axis. Therefore interferometer can actually work as a the shearometer, if the interfering points belong to the same surface, and it will measure the difference of displacement components. Otherwise, if a still surface is placed near the investigated surface, the interferometer is sensitive to the "absolute" displacement components. In the experiments reported in the present paper the interferometer was used for retrieving the absolute displacements, and

the reference surface is a L-shaped plate, as shown in Fig.2.

3 Measurement of **3D** displacements

Measurement of 3D deformation fields requires the evaluation at each point of three displacement components. Speckle interferometry techniques allow measuring a single displacement component by means of an "absolute" interferometer working with a single illumination and observation direction [21]; actually the same effect can be reached with a shearometer working with a fixed reference surface. Thus by three non-coincident illumination directions the displacement can be fully resolved in all its components.

If at a generic point the illumination and observation directions are known and identified by the unit vectors \mathbf{k}_i and \mathbf{k}_o , respectively, the sensitivity vector \mathbf{K} can be evaluated by the well-known formula of the holographic interfeometry:

$$\boldsymbol{K} = \boldsymbol{k}_o - \boldsymbol{k}_i \,. \tag{3}$$

The phase variation ϕ due to the generic 3D displacement $d=\{u, v, w\}$ can be evaluated as:

$$\phi = \frac{2\pi}{\lambda} \mathbf{K} \cdot \mathbf{d} = , \qquad (4)$$

$$\frac{2\pi}{\lambda} \left(K_x \ u + K_y \ v + K_z \ w \right)$$

where λ is the wavelength of the light source used in the experiments. Hence if three linearly independent sensitivity vectors are available, as shown in Fig.6 which represents schematically the operating conditions of the present interferometer, the vector dcan be fully resolved on the whole investigated area. If the three phase measurements $\{\phi_1, \phi_2, \phi_3\}$ are carried out at each point the 3D displacement can be resolved by the following expression, written in matrix form:

$$\begin{cases} \phi_1 \\ \phi_2 \\ \phi_3 \end{cases} = \frac{2\pi}{\lambda} \begin{bmatrix} K_{1x} & K_{1y} & K_{1z} \\ K_{2x} & K_{2y} & K_{2z} \\ K_{3x} & K_{3y} & K_{3z} \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}.$$
 (5)

The unique condition for solving the linear system of equations (5) is that the determinant of the matrix is different from zero, i.e. the three illumination directions must be linearly independent. In case of the present interferometer the observation direction is orthogonal to the investigated surface, while the angle θ indicated in Fig.6 is chosen equal to 30° for all the three illumination directions, and the sensitivity vectors lie in the planes *xz* and *yz*.

By applying eqs.(3) and (5) in the aforementioned operating conditions, the following expression for the displacement components is obtained:

$$\begin{cases} u \\ v \\ w \end{cases} = \frac{\lambda}{2\pi} \begin{bmatrix} \frac{2\sqrt{3}}{3} & \frac{\sqrt{3}}{3} & \frac{\sqrt{3}}{3} \\ 0 & \frac{\sqrt{3}}{3} & -\frac{\sqrt{3}}{3} \\ 0 & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{bmatrix}.$$
(6)

If the illumination is not obtained by a collimated beam, its divergence should be taken into account and the components of the sensitivity vectors become functions of the spatial coordinates. In this case the matrices of eq.(5) or eq.(6) must be evaluated at each point by taking into account the actual geometry of the setup, i.e. the location of the light source with respect to the orientation and position of the investigated surface. This effect can be neglected if the distance between the light source and the observed area is negligible if compared with the maximum dimension of the observed area.



Fig.6. Sensitivity vectors for measuring the three displacement components.

If the geometry of the setup does not allow neglecting the variation of the sensitivity vector along the observed area, this effect can be easily evaluated by straightforward mathematical expressions. In particular, according to the geometry reported in Fig.7, if a spherical wavefront is located on the *xz* plane at an horizontal distance *L* from the origin of the reference system, and the light propagation occurs along a direction forming at the origin of the reference system an angle of 60° with respect to the vertical direction (as it happens in the interferometer presented in the paper), the

sensitivity vector, after some mathematical manipulations of eq.(3), assumes the following expression:

$$K = \left\{ \frac{L - x}{A}, -\frac{y}{A}, \frac{L}{A\sqrt{3}} + 1 \right\},$$
with $A = \sqrt{(x - L)^2 + y^2 + L^2/3}$, (7)

where the coefficient *A* represents the distance between the location of the spherical wavefront and the origin on the reference system. In this expression the observation direction is assumed constant, but also this assumption could be easily removed. If this effect is taken into account, as above mentioned, the matrix of eq.(6) must be evaluated point by point, otherwise the evaluation of the elements of matrix can be carried out by means of eq.(7), evaluated at the origin of the coordinate system. In this last operating condition the values for the components of sensitivity vectors are the following:

$$K_{1x} = K_{2y} = -K_{3y} = \frac{\sqrt{3}}{2} = 0.866$$

$$K_{1y} = K_{2x} = K_{3x} = 0 , \qquad (8)$$

$$K_{1z} = K_{2z} = K_{3z} = \frac{3}{2} = 1.5$$

which can be assumed as reference values for evaluating their variation along the observed area. It is worthwhile mentioning that the maximum absolute value for a component of a sensitivity vector in interferometry is 2.

Figure 8 reports the contour plots in the plane xy that represent the loci of constant error of the components of the sensitivity vectors. Due to the symmetry of the illumination geometry, by three plots it is possible to evaluate the error for all the nine components of the sensitivity vectors, provided that the x and y coordinates are properly exchanged or reversed. In figure the spatial coordinates x and yare evaluated as fraction of the length L. In the case of the actual geometry of the interferometer the length L is about 55 mm and the investigated area about $8x6 mm^2$, hence the maximum range assumed for the ratios x/L and y/L is about 0.15. In figure the area corresponding to a maximum range for the ratios x/L and y/L of 0.2 is emphasized; within this, which overestimate the real working area of the interferometer, the maximum variations observed do not exceed 0.02 for the components K_{1x} , K_{2y} and K_{3y} , 0.1 for the components K_{1y} , K_{2x} and K_{3x} , and 0.04 for the components K_{1z} , K_{2z} and K_{3z} .



Fig.7. Geometry for evaluating the variation of the components of the sensitivity vectors.

When the 3D displacement field is measured by speckle interferometry, this is usually superimposed to a rigid body motion of the whole investigated area, which is normally an unwanted effect for several reasons. First, it is not easy to identify the absolute fringe order especially for a 3D problem, that requires the knowledge of three absolute fringe orders; sometimes it is possible to know the displacements of some points of the observed area, but it is not a common working condition, in particular when the measurements are carried out on small regions. Moreover, when the mechanical behavior of a material is investigated rigid body motions could make difficult identifying the desired information, whereas the strain components, computable by differentiating the displacement vector with respect to the spatial coordinates, would be unaffected by this drawback.

If the spatial distribution of the vector d is evaluated in the xy plane, the strain components can be computed according to the well-known equations of the theory of elasticity:

$$\varepsilon_{x} = \frac{\partial u}{\partial x} \quad \varepsilon_{y} = \frac{\partial v}{\partial y} \quad \gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

$$\varepsilon_{z} = \frac{\partial w}{\partial z} \quad \gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \quad \gamma_{zx} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}.$$
(9)

Actually only the first row of eqs. (9) can be evaluated, because the variation along the *z* coordinate cannot be retrieved by an speckle technique. Nevertheless, due to the plain stress conditions occurring on a free load surface [22], the components γ_{yz} and γ_{zx} are zero everywhere, while ε_z can be evaluated by the following equation:

$$\varepsilon_z = -\frac{\nu}{1-\nu} (\varepsilon_x + \varepsilon_y), \qquad (10)$$

where v is the Poisson's ratio of the material.







Fig.8. Variation of the components of the sensitivity vectors with respect to the non-dimensional coordinates x/L and y/L on the investigated area.

Two final remarks must be made about the evaluation of strain components. The first one concerns with the smoothness of the measured quantities. The differentiation amplifies the noise usually high when speckle interferometry is applied for measuring deformations, hence filtering [23] or fitting [24] the experimental data should be performed. Secondly, if the investigated area is not planar the strain evaluation could be difficult, because the shape of the surface must be taken into account in the analytical formulation.

Therefore the post-processing of the experimental data in speckle interferometry is normally an important phase of the overall measurement process, and it is strictly dependent on the specific problem which must be approached. For this reason a general-purpose software for analyzing experimental data hardly suites all the needs of users of interferometric techniques. Consequently who tries his hand at speckle techniques should also plan proper post-processing procedures of the experimental data, if accurate and "actual" full-field measurements are required.

4 Measurement procedure and results

In order to evaluate the three components of displacement it is necessary to acquire, for each component, the speckle pattern before and after the specimen has undergone the deformation field; it is hence necessary to switch on and off the diodes in turn.

Schematically, the measurement procedure is carried out according to the following steps.

- 1. Adjust the light intensity of each laser diodes. This operation requires to set the voltage of each diode in order to obtain a modulation able to guarantee accurate measurements.
- 2. Set the undeformed configuration. Speckle techniques allow measuring deformations occurring with the respect of a reference configuration, thus it is necessary to fix it.
- 3. *Switch on the first diode and off the others.* The investigated area must be illuminated only by a single light source whose position together with the observation direction define the single sensitivity vector.
- 4. Save a number of frames of the underformed configuration. Application of phase-shifting procedures requires to vary of known entities the optical path on one of the two arms of the interferometer. Increasing the number of steps (no less than three) allows improving the accuracy of the measurements. Obviously for

each step an image of the investigated area must be stored and then analyzed.

- 5. *Repeat steps 3 and 4 with the second and third diode.* In order to store the images relative to second and third component of displacement the same operations must be performed by illuminating the specimen with the other two lasers.
- 6. *Set the deformed configuration.* After storing of an image for each phase step and for each component, the deformation is applied to the specimen.
- 7. *Repeat steps 3, 4 and 5 in the deformed configuration.* The same operations must be repeated after the specimen undergoes the deformation which must be evaluated.
- 8. *Evaluate the phase maps.* For each component the phase is evaluated by well-known phase-shifting formulas [6], both in the deformed and undeformed configuration. Hence the phase map of each component is evaluated by subtracting pixel-by-pixel the phases of the two configurations.
- 9. Unwrap the phase maps. Because of the displacements are proportional to the phase see eq.(4) the phase maps must be unwrapped in order to remove the phase jumps by proper algorithm, able to work in noisy conditions intrinsic to speckle interferometry [25].
- 10. *Fit the phase maps*. As said in step 9 speckle interferometric data are very noisy, thus the unwrapped experimental data were fitted by the procedure proposed in [24].

The experiments were carried out on a specimen constituted by an aluminum plate moved by a 3 degree of freedom PZT actuator. The specimen is fixed to the interferometer along four rods, two of which fix the position of the reference surface. Obviously the actuator of the specimen is different from the actuator of the interferometer. The former is an expensive commercial device (Physik Instrumente, actuator S-316.10, amplifier E-503.00, servo-controller E-509.S3, digital interface E-515), working in closed loop configuration and able to perform with nanometric accuracy tilting up to 1.2 mrad and displacement up to 12 μ m. The latter is a cheap device designed, realized and calibrated with the aim of being integrated in the interferometer proposed in the present paper.

All the steps relative to the experimental acquisition of the data (steps 1 to 7) were controlled in LabVIEW environment by means of virtual instruments implemented on purpose. The control panel of the main virtual instrument is reported in

Fig.9. By the three controls Diode # the voltage (in volt) and so the light intensity of each diode laser is changed. The six controls Pos#1_PZT#2 define the specimen deformation, where #1 refers to undeformed (0) or deformed (1) configuration, and #2 refers to the displacement imposed to the single PZT used to move the specimen. The three boolean controls Component # allow selecting which component must be measured, while by the control Save steps it is possible to decide if save or not the phase steps in the path specified by the string control Step path.

The remaining steps of the measurement procedure (steps 8 to 10) were carried out in Mathematica environment. These operation could be performed also by implementing proper LabVIEW routines, but a standard programming language, like Mathematica or Matlab, allows more flexible operations on data like the images stored during the experimental tests.



Fig.9. Control panel of the virtual instrument implemented in LabVIEW.

The first experiments were carried out by imposing to the specimen the displacement field reported in Fig.10. Two rotations of the observed surface were imposed: the first, α_y , around an horizontal axis, which implies out-of-plane

displacements linearly variable along a direction perpendicular to the y-axis; the second, α_z , around a vertical axis, which implies circumferential in-plane displacements linearly variable from 0, at the origin of the axes, to a maximum value, at the most peripheral point of the observed surface.



Fig.10. Displacement field imposed to the specimen.

Three sets of experimental data obtained at different level of deformation are reported in Fig.11. The phase maps belonging to the same row refer to the same level of deformation, while the maps of the same column refer to the same displacement component.



Fig.11. Three sets of experimental data at different deformation levels.

The data reported in Fig.11 are then unwrapped and fitted. The fitted data are reported in Fig.12. In the first column the modulus of the in-plane displacement is reported, while the second column represents the out-of-plane component. The contour plots are drawn with a displacement increment of 100 *nm*. For each deformation level three tests were carried out and reported in Fig.12. It is possible to notice the high repeatability of the measurements. Furthermore, a lost of accuracy can be observed in the lower part of the plot relative to the maximum deformation level of the in-plane modulus. It derives from the intrinsic noise of the speckle techniques, i.e. the decorrelation [26], which increases gradually with the deformations, until eventually the phase information is completely destroyed.



Fig.12. Fitted data at three different deformation levels. The first column represents the modulus of the in-plane displacement, the second column the out-of-plane component. The displacements are given in nm.

A final remark on the contour plots concerns their shape, that is the non-perfect circularity and rectilinearity of the two types of plots. This is due to the systematic error introduced by the variation of the sensitivity vectors across the investigated area. The spatial variation of the components of the sensitivity vectors can be taken into account analytically, if the exact position of the light sources and of the point of view is known with respect to the investigated area. Alternatively an experimental approach can be adopted, by calibrating the interferometer measuring a known deformation.

6 Conclusions

In the paper the authors present a device working on the principle of speckle interferometry for deformation fields. measuring the The interferometer was designed and assembled with the aim of obtaining a low cost and portable device for the analysis of the mechanically induced deformations on small areas. Therefore it is particularly suitable for investigating problems in which high gradients of displacement are contained in small areas, such as residual stress measurement or analysis of the deformations around a crack tip.

The paper presents the first experimental results obtained by imposing a 3D rigid body motion to the specimen by means of a 3 degree of freedom PZT actuator. The results have shown a very high repeatability and a slight dependence on the variation of the sensitivity vectors across the investigated surface.

The device proposed is susceptible of a further substantial improvement. In particular the illuminations in the present design cannot work simultaneously, and the separate phase maps must be acquired in deferred times, by acting on the electronics. This drawback control can be straightforwardly overcome by using three illumination sources with different wavelengths, and acquiring the interferograms with a CCD color camera. In fact the spectral response of a color camera can be used to select the proper wavelength. way by one color image three In this monochromatic images are obtained, each of which can be used to determine a single phase map and, consequently, a single displacement component. When three different wavelengths are used simultaneously for illuminating the investigated area, the application of the phase-shifting procedure requires that the entity of the phase-shifts be chosen properly, in order to obtain well conditioned linear system of equations.

This improvement requires that the B&W camera is substituted with a color camera and that two of the three red laser diodes (wavelength about 660 nm) are replaced by a green and a blue one. It must be noticed that the diodes emitting in the blue line (wavelength about 405 nm) are starting to be available on the market at cheap prices, and that these diodes are housed in the same packages as the red ones. On the other hand the green sources are not available in the same layout; in fact, the typical green laser is obtained by doubling the frequency of a (cheap) diode emitting at 1064 nm; it is hence necessary to equip with a non-linear crystal to perform the doubling operation. Furthermore, apart from the non standard packaging necessary for this type of laser, the emission is different, too: by the standard housing (5.6 *mm* or 9.0 *mm* packaging system) the diodes produce a divergent and elliptical beam, while the beam outgoing from the duplication crystal is unexpanded; this fact implies the use of additional optical component.

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