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HOLOGRAFSKA INTERFEROMETRIJA I NJENA PRIMENA U BESKONTAKTNIM ISPITIVANJIMA

HOLOGRAPHIC INTERFEROMETRY AND ITS APPLICATION IN CONTACTLESS TESTING

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- contactless testing

Izvod

Zahvaljujući razvoju kompjuterske tehnike i digitalnih kamera holografska interferometrija nalazi sve veću primenu u industrijskoj metrologiji. Na osnovu laserske tehnike i interferometrije razvile su se spekle interferometrija, širografija i moare interferometrija. U radu je dat kratak pregled ovih metoda i njihova primena kao metoda bez razaranja za beskontaktna ispitivanja.

Abstract

Thanks to the development of computers and digital cameras holographic interferometry is intensively applied in industrial metrology. Based on laser techniques and interferometry the speckle interferometry, shearography, and moiré interferometry have been developed. The paper shortly presents these methods and their application as contactless method for non-destructive testing.

UVOD

Holografija i holografska interferometrija (HI) su metode koje se široko primenjuju u laboratorijama, a imaju i značajnu industrijsku primenu za ispitivanja bez razaranja (IBR).

Razvijeno je više metoda holografisanja. Najčešće se primenjuje optička holografija koja koristi lasersku svetlost u vidljivom delu spektra, /1/. U klasičnom postupku se interferencijski efekti laserske svetlosti (monohromatske ili bele) snimaju na foto ili na termoosetljivim emulzijama. Elektronska holografija koristi digitalne kamere. U nekim posebnim slučajevima se koriste akustička, mikrotalasna, holografija sa elektronskim snopom ili X-zracima ili kompjuterska holografija. Sa sličnim mogućnostima se, pored holografske interferometrije, danas koriste: spekle interferometrija, moare interferometrija i širografija.

U ovom radu su izloženi osnovni principi HI s posebnim osvrtom na primenu u ispitivanjima bez razaranja (IBR). Prikazani su rezultati sopstvenih istraživanja u Vojnotehničkom institutu (VTI) iz Beograda i karakteristični primeri iz literature, iz oblasti ispitivanja strujanja fluida, oblika i dimenzija objekata, analize grešaka, i analize napona i deformacija u konstrukcijskim komponentama.

OSNOVI HOLOGRAFIJE I HOLOGRAFSKE INTERFEROMETRIJE

Informacije o nekom predmetu svetlost može da prenese kao modulacije amplitude, faze, frekvencije ili polarizacije. Holografija omogućava da se istovremeno sačuvaju informacije o amplitudi i fazi, što se postiže interferencijom predmetnog i pomoćnog, uniformnog snopa svetlosti.

INTRODUCTION

Holography and holographic interferometry (HI) are intensively applied in laboratories, but they are also important for non-destructive testing (NDT) in industrial applications.

Several holographic methods have been developed. Most frequently used is optical holography, using laser light in visible spectrum, /1/. In classical procedures the interferential effects of laser light (monochromatic or white) are recorded on photo or thermosensitive emulsions. Electronic holography uses CCD cameras. In some specific cases acoustic and microwave holography, with electron beam, X–ray, or computer holography can be used. With similar possibilities, in addition to holographic interferometry, today are applied: speckle interferometry, moiré interferometry and shearography.

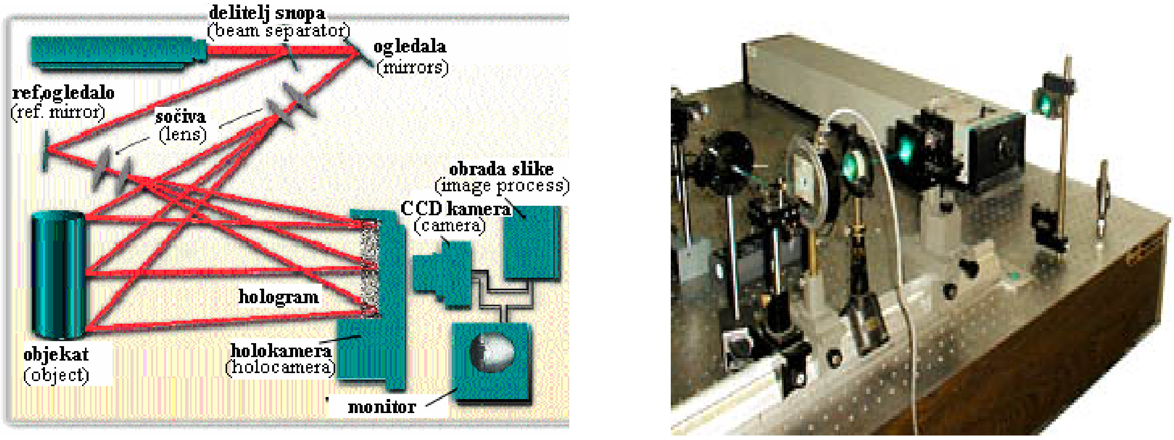
In this paper the basic HI principles are presented with special attention to non-destructive testing (NDT) application. The results of own researches, performed at the Military Technical Institute (MTI) in Belgrade and typical examples from references obtained from fluid flow tests, shapes and sizes of objects, defect analyses, and stress and strain analyses in structural components are presented.

FUNDAMENTALS OF HOLOGRAPHY AND HOLOGRAPHIC INTERFEROMETRY

Light carries information about a particular object as modulations of amplitude, phase, frequency or polarization. Holography enables to record at the same time both data about amplitude and phase and this is achieved by interference of the object- and auxiliary uniform light beam.

Zapis ove interferencije predstavlja hologram koji sadrži skrivenu sliku objekta. Ovo je prvi deo holografskog procesa /2, 4/. Hologram se osvetljava laserskom svetlošću (može i belom) da se vidi šta je snimljeno. Difrakcija svetlosti je u osnovi drugog dela procesa, rekonstrukcije slike, odnosno skrivenog lika holograma. Lik je prostorni, može da se posmatra pod raznim uglovima sa rezolucijom do 3000 linija/mm, da se rekonstruiše i samo na osnovu delova holograma, da se uvećava ili smanjuje. Eksperimentalni rad u ovoj oblasti zahteva iskustvo, posebne uslove i opremu. Na sl. 1 je prikazan proces snimanja i rekonstrukcije holograma (a), i deo holografskog interferometra u VTI (b) /2, 4/.

The record of this interference is a hologram which contains a hidden image of the object. This is the first part of the holographic process /2, 4/. The hologram is lit by laser light (could also be white) to see what is recorded. Light diffraction is the basis of image reconstruction, i.e. hidden image on the hologram. The image is spatial, can be viewed under different angles with resolutions up to 3000 lines/mm, can be reconstructed using only segments of the hologram, and can be zoomed in or out. Experimental work in this field requires experience, special conditions and equipment. Figure 1 shows the procedure of hologram recording and reconstruction (a) and part of holographic interferometer at MTI (b), /2, 4/.



Slika 1. Snimanje i rekonstrukcija holografskog lika (levo) i komponente laboratorijskog holografskog interferometra (desno)
Figure 1. Recording and redesign of holographic image (left) and components of laboratory holographic interferometer (right).

Ako se snime dva holograma istog predmeta na istom nosiocu zapisa, u procesu rekonstrukcije doći će do istovremenog pojavljivanja oba lika. Likovi su koherentni vremenski i prostorno, pa međusobno interferišu. Ako su identični pojaviće se samo lik predmeta. Ako je došlo do neke promene na predmetu u intervalu pre eksponiranja, rekonstruisani lik biće prekriven interferencionim linijama, koje opisuju nastale promene. Dobijeni lik predstavlja holografski interferogram, /2/.

Holografska interferometrija omogućava da se vide promene na površini objekta koji je netransparentan za talasnu dužinu izabrane svetlosti ili promene u celoj zapremini, ako je objekt transparentan. Unutrašnje promene HI može da „vidi“ indirektno. Na primer, ako se objekt sa greškom izloži dejstvu mehaničkog ili toplotnog opterećenja, ili vibracijama, može da se pojavi neregularna promena na površini objekta u okolini greške. Ako se jedan hologram snimi pre, a drugi u toku (ili posle) opterećenja, dobijeni likovi interferišu i unutrašnji defekti postaju vidljivi. Ako ne postoje greške u objektu, promene zbog dejstva opterećenja uzrokovaće jednolične interferencijske linije kao rezultat ravnomernih promena jednog ili više elemenata objekta, a ako postoje greške, linije će biti složenog oblika i neravnomerne.

Najviše korišćene interferometrijske tehnike su: metoda dvojne ekspozicije, metoda ispitivanja u realnom vremenu, vremenski usrednjena metoda, „sendvič“ metoda, refleksiona i fazna, s konačnim i beskonačnim interferencijskim linijama, interferometrija sa dva i više snopova svetlosti, sa jednom ili više talasnih dužina itd.

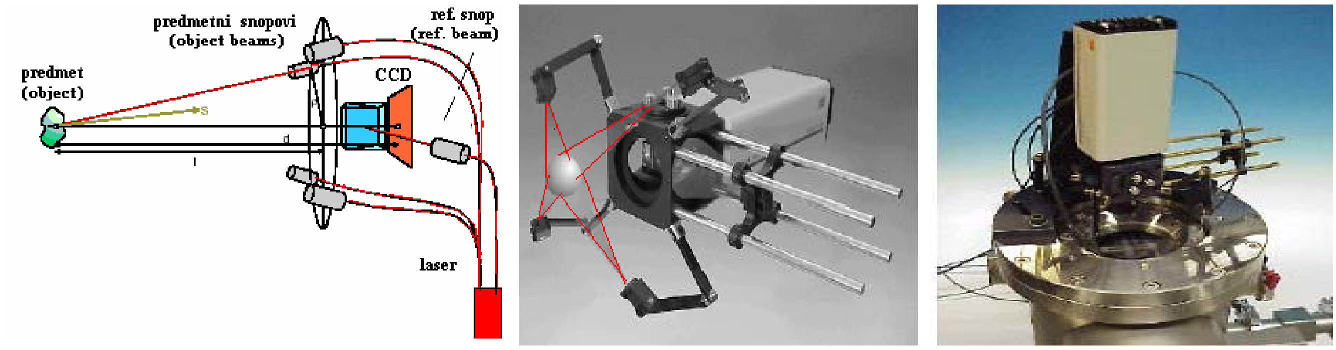
When two holograms of the same object are recorded on the same record plate, in the reconstruction procedure both images will occur at the same time. The images are coherent in time and space, so they interfere mutually. If they are identical only the object image will occur. If some changes take place in the time interval between exposures, the reconstructed image will be covered by interferential lines that depict involved changes. The obtained image represents a holographic interferogram, /2/.

Holographic interferometry enables visibility of changes on the surface of the object that is non-transparent for wave length of selected light or changes in total volume when the object is transparent. HI can indirectly “see” inner changes. For example, if the defected object is exposed to mechanical or thermal loads, or to vibrations, irregular changes can appear on the object surface in the vicinity of the defect. If one hologram is recorded before, and another during (or after) loading, the obtained images interfere and inner defects become visible. If there are no defects in the object, changes due to loading will cause uniform interferential lines as a result of changes of one or more elements on the object, and if defects do exist, the lines will be of complex shape and non-uniform.

Mostly used interferometric techniques are: method of double exposition, the real time method, time averaged method, “sandwich” method, reflexion and phase methods, with finite and infinite interferential lines, interferometry with two or several light beams, with one or several wave lengths and so on.

Postoji niz drugih interferometrijskih tehnika koje su se razvile kao modaliteti HI zahvaljujući razvoju optoelektronike. Pre svega tu treba navesti elektronsku ili digitalnu holografsku interferometriju (holografija EHI/DHI). Principska shema i digitalni interferometar sa četiri snopa su dati na sl. 2a,b i c. Deo laserskog snopa osvetljava predmet koji se ispituje. Digitalna kamera simultano prima svetlost rasejanu od predmeta i referentni snop koji ide direktno. Ova tehnika ima iste karakteristike kao klasična HI, a funkcioniše bez korišćenja posrednog medijuma za snimanje holograma. Danas su na tržištu dostupni prenosivi digitalni holografski interferometri koji se mogu koristiti u industriji, montirani na uzorku koji se ispituje.

There is a series of other interferometry techniques that are developed as HI modalities due to the development of optoelectronics. First of all, electronic or digital holographic interferometry (EHI/DHI holography) must be mentioned. A principal scheme and a digital interferometer with four beams are given in Figs. 2a, b, c. A part of laser beam lights the tested object. The CCD camera simultaneously receives light dissipated from the object and the direct referent beam. This technique has the same characteristics as classical HI but operates without indirect hologram recording media. Today, portable digital holographic interferometers are available on the market which can be used in industry, applied on the tested sample.



a b c

Slika 2. a) Principi digitalne HI, b) digitalni HI sa četiri snopa, c) interferometar montiran na testiranom prozoru, /12/
Figure 2. a) Principles of digital HI, b) Digital HI with four beams, c) Interferometer applied on a tested window, /12/.

ELEKTRONSKA SPEKLE INTERFEROMETRIJA (ESPI)

Elektronska spekle interferometrija (ESPI) se koristi za snimanje spekle interferograma. Fenomen spekle (mrljice) se javlja kada se hrapava površina osvetli koherentnom laserskom svetlošću. Mrljice nastaju zbog interferencije zrakova rasejanih na različitim tačkama predmeta. Amplituda svetlosti na površini objekta je promenljiva. Slučajna raspodela intenziteta predstavlja spekle efekt, koji se snima CCD kamerom (sl. 3a) u koju se unosi referentni laserski snop. Rezultat interferencije se memoriše direktno na računaru. Dobijaju se specifične interferencijske linije koje opisuju stanje objekta u datom trenutku. Istom tehnikom se snima i drugi spekle interferogram koji se od prvog razlikuje ako je došlo do nekih promena na objektu. Drugi interferogram može da se dodaje prvom ili se oduzima od njega. Rezultirajući interferogram ima korelacione pruge koje opisuju nastalu promenu. Obrada rezultata se odvija pod kontrolom specijalnog softvera, veoma je brza i omogućava posmatranje promena u realnom vremenu. Mogu da se koriste i brze kamere ako se prate izuzetno brze ili kratkotrajne pojave, /7/. Rezolucija ESPI je manja od klasične HI, koja zavisi od karakteristika CCD kamere i kapaciteta računara. Primena ESPI za ispitivanje podloge za železničke šine data je na sl. 3b, /9/.

ELECTRONIC SPECKLE INTERFEROMETRY (ESPI)

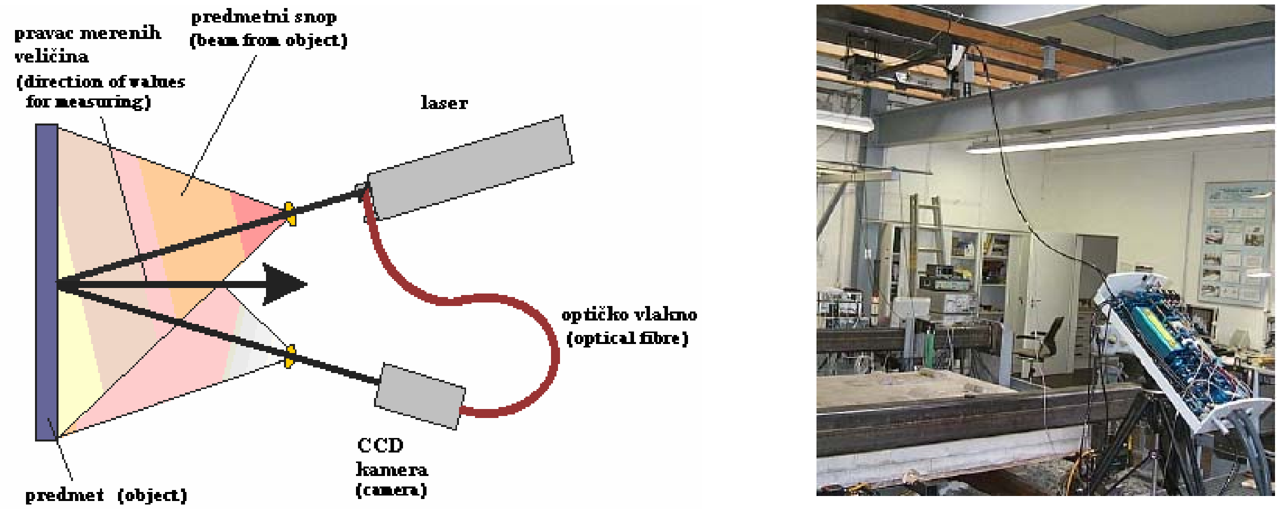
Electronic speckle interferometry (ESPI) is used for recording speckle interferograms. The speckle phenomenon occurs when rough surface is lit by coherent laser light. Speckles appear due to interference of beams dissipated at different spots on the object. The light amplitude on the object surface varies. Random distribution of the intensity is a speckle effect which is recorded with CCD camera (Fig. 3a) in which a referent laser beam is involved. The interference result is directly stored in the computer. Typical interferential lines are obtained, describing the object state in a given instant. By using the same technique a second speckle interferogram is recorded that differs from the first one if certain changes on the object had occurred. The second interferogram can be superimposed to the first one or subtracted from it. The resulting interferogram contains correlation fringes describing the occurred change. The results are process controlled by special software. It is very fast and monitors changes in real time. High speed cameras can also be used if extremely fast or short events are traced, /7/. The resolution of ESPI is smaller than that of classical HI which depends on CCD camera characteristics and computer capacity. The application of ESPI for testing rail track ties is given in Fig. 3b, /9/.

ŠIROGRAFIJA

Širografija (SG) je laserska merna metoda koja ima dosta sličnosti sa HI i ESPI. Osnovna razlika je to što SG meri gradijente promena koji nastaju na površini objekta, a ne same promene.

SHEAROGRAPHY

Shearography (SG) is a laser measuring method similar to HI and ESPI. The basic difference is that SG measures gradients of change occurring on the object surface but not changes themselves.



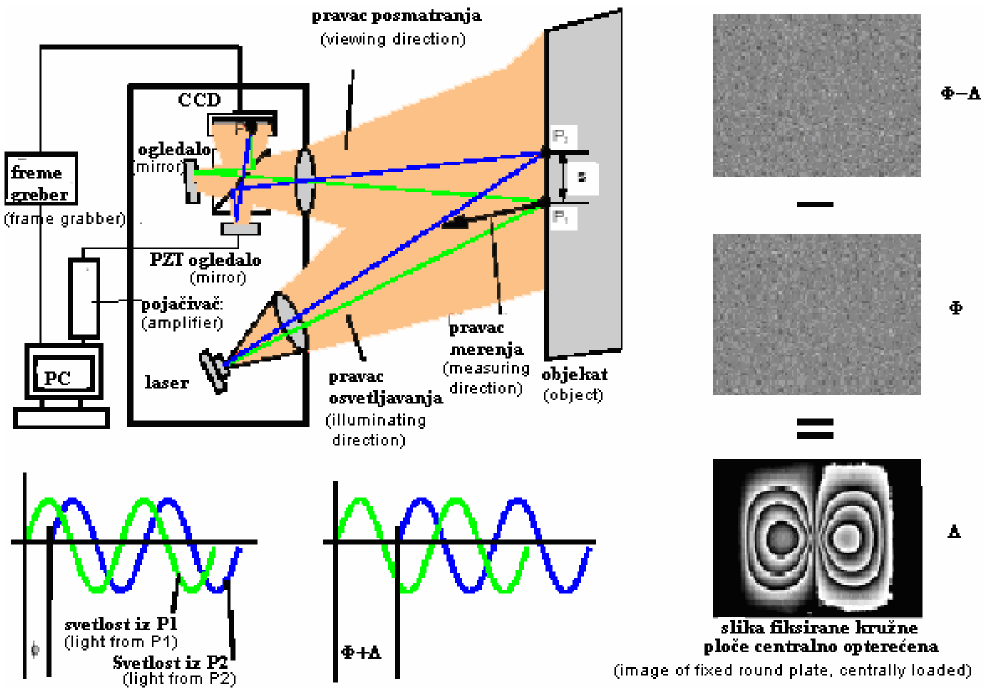
Slika 3. Šematski prikaz principa ESPI (levo) i sistem za ispitivanje pragova za železničke šine (desno) /9/
Figure 3. Schematic presentation of ESPI principle (left) and system for rail track tie testing (right) /9/.

Interferencijski efekti koji se javljaju na slici su funkcije napona. Sa širograma mogu direktno da se lociraju greške koje su dovele do promena gradijenta napona u objektu. Na sl. 4a je šematski data postavka i princip rada ove metode. Njena specifičnost je što umesto referentnog snopa za interferenciju koristi uređaje pomoću kojih svetlost iz dve tačke na objektu dovodi u jednu tačku u ravni slike, gde oni interferišu i daju spekle interferogram. Uređaj prikazan na sl. 4 koristi Majkelsonov interferometar. Interferogram se snima digitalnom kamerom i upućuje u računar.

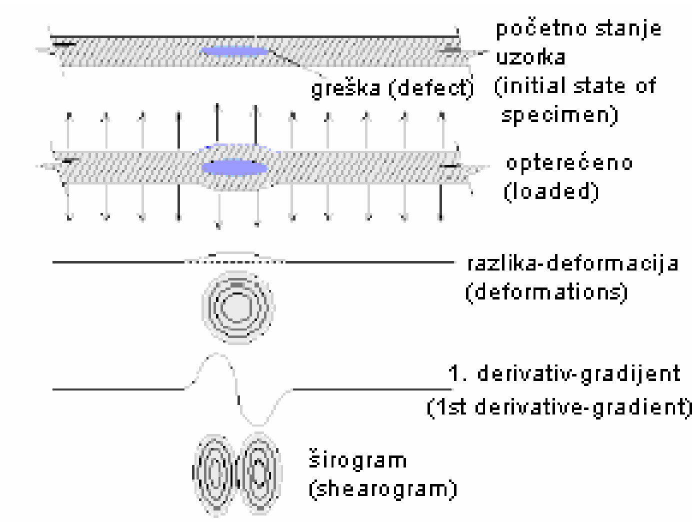
U ispitivanjima ovom metodom se takođe snimaju dva širograma. Oni se pomoću adekvatnog softvera oduzimaju i dobijena slika daje samo gradijente promena nastalih između ekspozicija. Na sl. 5 su date razlike u slikama istog uzorka snimljeni sa HI i SG.

Interferential effects occurring on the image are stress functions. It is possible to directly locate defects causing the change of stress gradient in the object. Figure 4a shows the disposition and operating principle of the method. It is typical for this method that instead of referent interferential beam the devices direct the light from two points on the object to one point in the image plane, where they interfere and produce the speckle interferogram. The device in Fig. 4 uses a Michelson interferometer. The interferogram is recorded by CCD camera and sent to a computer.

Two shearograms are recorded with this method. They are subtracted by adequate software and the obtained image shows only gradients that occurred between exposures. Differences in images of the same samples recorded by HI and SG are presented in Fig. 5.



Slika 4. Princip širografije (levo) i dobijanje širograma (desno)
Figure 4. Principle of shearography (left) and development of shearogram (right).



Slika 5. Razlika između holografije i širografije
Figure 5. The difference between holography and shearography.

RAZVOJ HOLOGRAFSKIH METODA

Zahtevi za veću preciznost, komfor rada i ekonomičnost doveli su do razvoja novih metoda kao što su /2, 6, 7/:
– moare interferometrija (digitalna moare, DMI);
– optička koherentna tomografija, korisna za ispitivanje transparentnih uzoraka (OCT);
– laser-ultrazvučna interferometrijska metoda (LUI), koja „vidi" kroz uzorke koji nisu transparentni u vidljivom delu spektra, jer koristi lasersku svetlost sa talasnom dužinom u oblasti ultrazvuka.

PRIMENA HOLOGRAFIJE I HOLOGRAFSKE INTERFEROMETRIJE

Osnovne metode holografije (HI, ESPI, DMI, SG, OCT, LUI) su beskontaktne i precizne zbog čega su primenljive u ispitivanju promena veličine od talasne dužine svetlosti do nekoliko centimetara, /6–13/.

Holografske interferometrija je dugi niz godina imala primat u laboratorijskim i industrijskim ispitivanjima i još uvek je dominantna u laboratorijskim ispitivanjima. Industrijska primena HI postavlja niz zahteva kao što su efikasnost, rad u realnom vremenu pri neadekvatnim uslovima, rad na terenu, jednostavnost opreme, ekonomičnost, uz često manju preciznost u odnosu na laboratorijska ispitivanja. Zbog toga su prvo zamenjene pločica sa foto emulzijom prikladnijim termoplastičnim pločicama, uz manju rezoluciju (do 2000 linija/mm) i mogućnost višekratne upotrebe (piši-briši). Glavni cilj poslednjih petnaest godina je da se potpuno eliminiše zapis interferencijske slike na nekom medijumu i da se interferencija snimi direktno digitalnom kamerom. Razvijeni su kompaktni, prenosivi holografski interferometri, umesto modularnih, laboratorijskih modela. Skupi laseri sa posebnim kvalitetom snopa (koherentna dužina, monohromatičnost, usmerenost i polarizacija) su zamenjeni diodnim laserima, koji su mnogo jeftiniji. Tako je došlo do razvoja metoda koji su u osnovi interferometrijske tehnike sa elementima holografije.

Brojni su primeri primene holografskih metoda ispitivanja: avionska i kosmička tehnika, industrija naoružanja,

DEVELOPMENT OF HOLOGRAPHIC METHODS

Requirements for higher accuracy, comfort and economy allowed to develop new methods such as /2, 6, 7 /:
– moiré interferometry (digital moiré, DMI);
– optical coherent tomography, useful for testing of transparent samples;
– laser-ultrasonic interferometry method (LUI) that can "see" through non-transparent samples in the visible spectrum using laser light with wave lengths in the range of ultrasound.

APPLICATION OF HOLOGRAPHY AND HOLOGRAPHIC INTERFEROMETRY

Basic holographic methods (HI, ESPI, DMI, SG, OCT, LUI) are contactless and accurate and so applicable in testing size changes from light wave lengths to several centimetres, /6–13/.

For many years holographic interferometry had priority in laboratory and in industrial testing being still dominant in laboratory tests. Industrial application of HI requests a series of conditions such as efficiency, operation in real time in non-adequate conditions, in-situ operation, simple equipment, economy, frequently followed by lower accuracy compared to laboratory testing. As a consequence, foils with photo-sensitive emulsion are replaced by moiré convenient thermoplastic foils of lower resolution (up to 2000 lines/mm) and possible multiple use (re-writeable foils). The main goal in the last fifteen years was to completely eliminate records of interferometric images on media and to directly record the interference with CCD camera. Compact, portable holographic interferometers are developed, replacing modular laboratory models. Expensive lasers with beams of extra quality (coherent length, monochromatic, directionality, and polarization) are replaced by much cheaper diode lasers. Consequently, this had lead to developing methods based on interferometric techniques, but with elements of holography.

There are numerous examples of applied holographic test methods: airplane and space structures, arms industry, automobilska i mašinska industrija, energetika, elektronika, procesna i hemijska industrija, građevinarstvo, medicina, čuvanje i održavanje objekata kulture, kao i u svakodnevnom životu (kreditne kartice, bar kodovi). Primeri primene prikazani su na sl. 6–11.

Laboratorije VTI za eksperimentalnu aerodinamiku i raketnu tehniku više od dvadeset godina koriste HI za ispitivanje napona u transparentnim uzorcima, u posudama pod pritiskom, vizualizaciju strujanja u aerotunelima i ispitivanje izduvnih gasova raketnih motora. Koristio se HI modularnog tipa sa rubinskim laserom (E = 3,5 J, t = 30 ns, λ = 694 nm, l_k > 2 m) za ispitivanje uzoraka prečnika do 900 mm.

Na sl. 6a je prikazan interferogram transparentne pločice od klirita snimljen metodom dvojne ekspozicije: za vreme prve, pločica je u prostoru gde prolazi predmetni snop, a u toku druge ekspozicije pločica je sklonjena sa puta svetlosti. Interferencione linije su jednake širine i pomoću njih se može odrediti oblik pločice. Na sl. 6b se vide izonaponske linije u staklenoj pločici snimljene pod različitim uglovima. Pločica je postavljena u nosač koji ima četiri šiljka za zatezanje, pomoću kojih je menjana sila između prve i druge ekspozicije.

Slika 7 prikazuje snimke strujanja vazduha oko rakete sa M = 1,56 i strujanje u radnom delu aerotunela u dvodimenzionalnom mlazniku raketnog motora sa M = 2,6 sa mogućnostima upravljanja vektorom potiska. Holografski interferogram omogućava direktno određivanje gustine vazduha (a preko gustine i drugih parametara fluida interesantnih za aerodinamička ispitivanja) za razliku od drugih optičkih metoda koje daju informacije o gradijentu gustine.

Slika 8 pokazuje kako se slika polja napona može koristiti za utvrđivanje grešaka.

Na sl. 9 prikazan je širogram dobijen ispitivanjem PVC cevi unutrašnjim pritiskom od 0,02 MPa.

Snimak elektronske spekle interferometrije (ESPI) se može iskoristi za proračun pomeranja (sl. 10).

Elektronski holografski interferogrami koji pokazuju grešku u plastičnoj ploči i plastičnoj cevi prikazani su na sl. 11.

ZAKLJUČAK

Interferometrijske tehnike (HI, ESPI, DMI, SG i druge) su perspektivne metode. Brzi tehnološki napredak omogućava optimizaciju metoda i otvara nove mogućnosti njihove primene. Veliki broj proizvođača danas u svetu nudi jeftine komercijalne sisteme, a dostupni su i specijalni sistemi sa strogo definisanom namenom, što omogućava intenzivnu primenu.

automotive and mechanical engineering industry, energy, electronics, processing and chemical industries, civil engineering, medicine, conservation and maintenance of cultural objects, as well as in everyday life (credit cards, bar codes). Examples are given in Figs. 6–11.

Laboratories for experimental aerodynamics and rocket technics at MTI have been using HI for testing stresses in transparent samples for more than twenty years, in pressure vessels, flow visualization in wind tunnels and testing exhaust fumes in rocket engines. The Hi of modular type is used with ruby laser (E = 3.5 J, t = 30 ns, λ = 694 nm, l_k > 2 m) for testing samples 900 mm in diameter.

Figure 6a shows the interferogram of a transparent plate recorded by two exposition methods: during the first, the plate is located in space where the object beam passes, and in the second exposition the plate is removed from the light trace. Interferential lines are of the same thickness, enabling to determine the plate shape. In Fig. 6b isostress lines in glass plate are visible, recorded under different angles. The plate is positioned in the support containing four bolts for tension, applied to change the load between the first and second exposition.

Figure 7 shows air flow images around a rocket with M = 1,56 and a wind tunnel flow test section in a two-dimensional jet engine nozzle of M = 2,6 with controllable pressure (jet) vector. The holographic interferogram enables direct determination of air density (and thus other fluid parameters interesting for aerodynamic tests) in contrast to other optical methods that give data of density gradients.

Figure 8 shows how the stress field image can be used for the detection of defects.

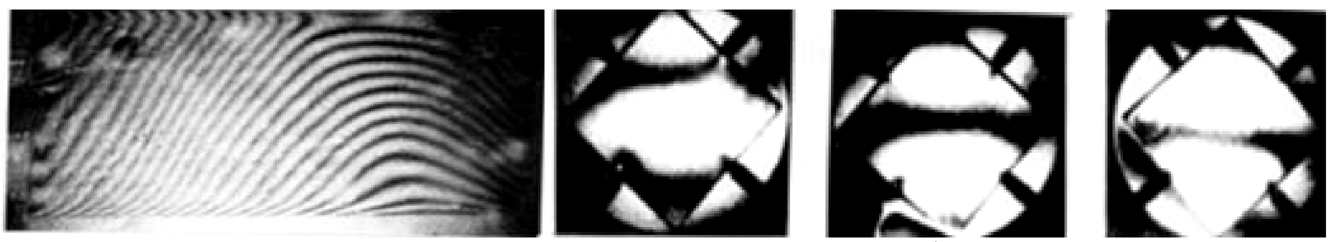
A sheargraph obtained by testing PVC tube with inner pressure of 0.02 MPa is presented in Figure 9.

The image of electronic speckle interferometry (ESPI) can be used to calculate displacements (Fig. 10).

Electronic holographic interferograms indicating defects in plastic plate and in plastic tube are presented in Fig. 11.

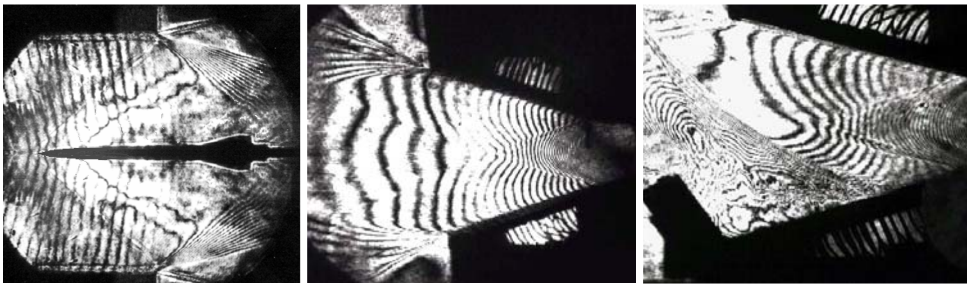
CONCLUSION

Interferometric techniques (HI, ESPI, DMI, SG and others) are perspective methods. Fast technological developments had enabled optimization of the methods and opened new possibilities of their application. A significant number of manufactures today in the world offer cheap commercial systems, and special systems with strictly defined applications are available, making possible intensive use.



a b

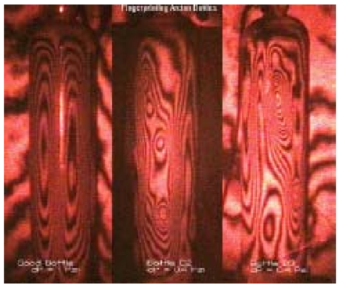
Slika 6. Rezultati ispitivanja holografskom interferometrijom uzorka transparentnog materijala, izloženog zatezanju, /3/
Figure 6. Results of testing a sample of transparent material exposed to tension by holographic interferometry, /3/.



a b c

Slika 7. Snimci strujanja oko rakete (a), u mlazniku raketnog motora bez prepreke (b) i sa preprekom (c), /4, 5/

Figure 7. Images of flow around rocket (a), in the nozzle of jet engine without obstacle (b), and with it (c), /4, 5/.

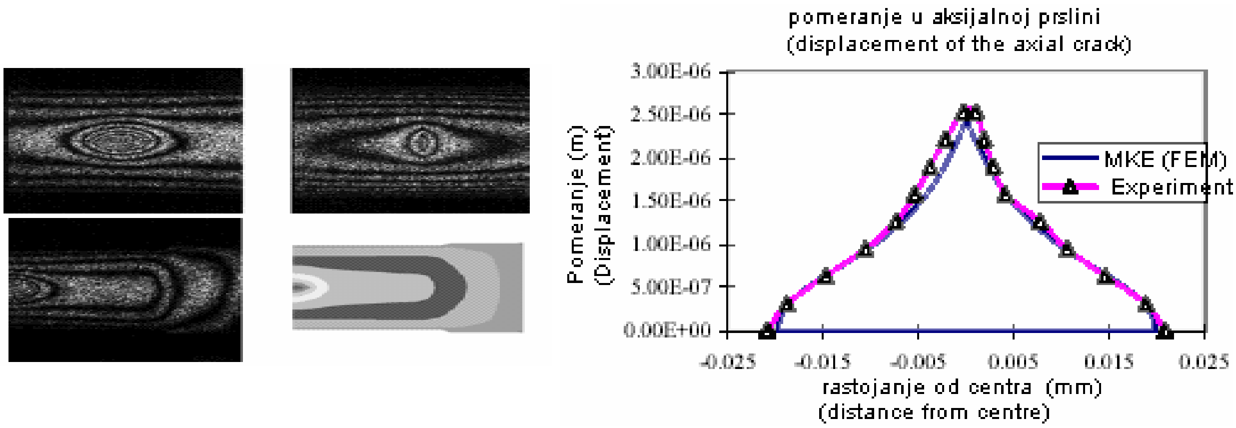


Slika 8. Hologrami ispitivanja boce pod pritiskom: prva nema, a druge dve imaju greške

Figure 8. Holograms of bottle pressure test: first is without and two others are with defects.

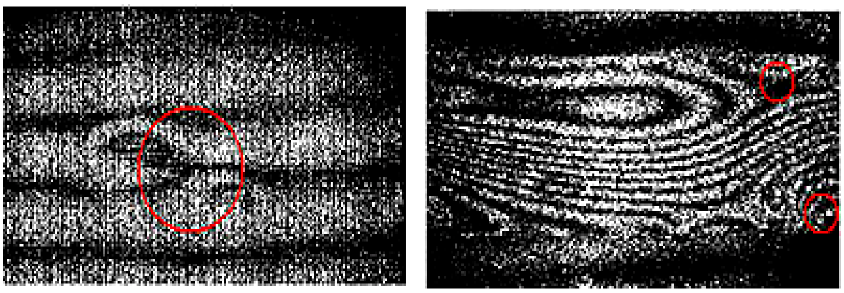
Slika 9. Širogram (levo) dobijen ispitivanjem PVC cevi (desno) pod unutrašnjim pritiskom od 0,02 MPa

Figure 9. A shearograph (left) obtained by testing a PVC tube (right) with inner pressure of 0.02 MPa.



Slika 10. Snimci elektronske spekle interferometrije (ESPI) i na osnovu njih proračunata pomeranja u ravni normalnoj na površinu cevi sa aksijalnim greškom

Figure 10. The image of electronic speckle interferometry (ESPI) and based on them, the calculated displacements in plane normal to the surface of the tube with an axial defect.



Slika 11. Elektronski holografski interferogrami, koji pokazuju grešku u plastičnoj ploči (levo) i u plastičnoj cilindričnoj cevi (desno)

Figure 11. Electronic holographic interferograms, indicating defects in plastic plate (left) and in plastic tube (right).

LITERATURA – REFERENCES

1. Born, M., Wolf, E., *Principles of Optics*, Pergamon Press, Oxford, 1983.
2. Vest C.M., *Holographic Interferometry*, Springer-Verlag, New York, 1980.
3. Ristić, S., *HI i njena primena u arhitekturi i građevinarstvu*, Zbornik sa seminara inženjera i tehničara arhitekture i građevinarstva Hrvatske, Zagreb, 1980, str. 56-72.
4. Ristić, S., *Holografija i njena primena u vizualizaciji strujanja*, VTG, br. 6, 1989, str. 635-642.
5. Ristić, S., *Disturbance of Transonic Wind Tunnel Flow by a Slot in the Tunnel Wall*, Exper. in Fluids, No. 11, 1991, pp. 403-405.
6. Stetson, K.A., Wahid, J., *Real-Time Phase Imaging for Non-destructive Testing*, Experimental Techniques, May/June 1998, Vol. 22, No. 3.
7. Moore, A.J., Hand, D.P., Barton, J.S., Jones, J.D.C., *Transient deformation measurement with electronic speckle pattern interferometry and a high-speed camera*, Applied Optics, 38, 1, 1999, pp. 1159-1162.
8. Dzuba, A.S., Grigoriev, V.D., Pisarev, V.S., *Comparison of the SC/NASTRAN and holographic interferometry data on a local strain/stress evaluation in the elasto/plastic range*, Moscow Institute of Physics and Technology Educational Scientific Experimental Centre, 16, Gagarina str., Zhukovsky, Moscow reg., 140160 Russia, 2003.
9. Lammering, R., Plenge1, M., Ettemeyer, A., Walz, Th., *Optical inspection technique for vibration analysis and defect indication in railway*, Universität der Bundeswehr Hamburg, Dantec Ettemeyer GmbH Ulm, 2002.
10. Yang, L.X., Hung, Y.Y., *Digital shearography for NDT and application in automotive and aerospace industries,* Department of Mechanical Engineering, Oakland University, Rochester, MI.
11. Ristić, S., Srećković, M., *Laser Application Possibilities in Production and Control of Aircraft Industry*, II International symposium, Light metals and Composite Materials, 19-20 May, 2004, Belgrade, Proceedings, pp. 151-154.
12. Findeis, D., Gryzagoridis, J., *Non-Destructive Testing of Composites using portable Laser based Methods,* Proc. ICCE/6 Sixth Annual International Congress on Condition Monitoring and Diagnostic Engineering Management, July 7th Suderland, Coxmor Publishing, Kingham, UK, 1999, pp. 409-415.
13. Findeis, D., Gryzagoridis, J., *Feasibility of Optical Interference-based NDE methods to Inspect Helicopter Rotor Blades,* Proc. SPIES 7th International Symposium on Non-Destructive Evaluation and Health Monitoring of Aging Infrastructure, March 5-9th 2000, Newport Beach, California USA.