Mechanisms and Machine Science 24

Paulo Flores
Fernando Viadero *Editors*

New Trends in Mechanism and Machine Science

From Fundamentals to Industrial Applications

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Editors

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From Fundamentals to Industrial Applications

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Preface

EUCOMES 2014 is the fifth event in a series that was started in 2006, under the Patronage of IFToMM, International Federation for the Promotion of Mechanism and Machine Science. The aim of the conference is to bring together European researchers, industry professionals, and students from the broad range of disciplines referring to Mechanism Science, in an intimate, collegial, and stimulating environment.

The EUCOMES conference began in February 2006 in Obergurgl (Austria), and has continued subsequently in Cassino (Italy) in September 2008, Cluj-Napoca (Romania) in September 2010, and Santander (Spain) in September 2012. The 2014 edition is organized by the Center for Mechanical and Materials Technologies (CT2M) and the Department of Mechanical Engineering (DEM) of the Engineering School of the University of Minho in Guimarães, Portugal, from 16 to 19 September 2014.

This book compiles the most recent research results in mechanism science, intended to reinforce and improve mechanical systems in a variety of applications in daily life and industry. This book is published under the Machine and Mechanism Science series and addresses issues related to: Theoretical kinematics, Computational kinematics, Mechanism design, Experimental mechanics, Mechanics of robots, Dynamics of machinery, Dynamics of multibody systems, Control issues of mechanical systems, Mechanisms for biomechanics, Novel designs, Mechanical transmissions, Linkages and manipulators, Micromechanisms, Teaching methods, History of mechanism science, and Industrial and nonindustrial applications.

EUCOMES 2014 received more than one hundred submissions, and after a rigorous review process by at least two reviewers for each paper, 100 papers were accepted for oral presentation at the conference and are included in this book.

We express our grateful thanks to IFToMM, Portuguese Association of Theoretical, Applied and Computational Mechanics (APMTAC), the Department of Mechanical Engineering of the University of Minho, the members of the International Scientific Committee for their cooperation: Prof. Bukhard Corves (Germany), Prof. Doina Pisla (Romania), Prof. Fernando Viadero (Spain), Prof. Jean-Pierre Merlet (France), Prof. Manfred Husty (Austria), Prof. Marco Ceccarelli (Italy),

Prof. Paulo Flores (Portugal), and Prof. Teresa Zielinska (Poland), the members of the Award Committee and the members of the Honorary Committee.

We also want to express our gratitude to all the authors for their interest in participating in EUCOMES 2014 and for writing the manuscripts in a timely manner, allowing this conference to be a reality in a short period of time.

We thank all anonymous and volunteer reviewers for their outstanding work, which allowed the Conference Springer Book to be published as scheduled.

We thank the University of Minho for hosting the EUCOMES 2014 conference and we express our deepest gratitude to The Local Organizing Committee: Eurico Seabra, João Mendonça Silva, José Machado, Luís Ferreira da Silva, Mário Lima, Nuno Peixinho, Paulo Flores (Chairman), Pedro Souto, and Sara Cortez.

Guimarães, June 2014 Paulo Flores
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Paulo Flores
Fernando Viadero

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An In Vitro Experimental Evaluation of the Displacement Field in an Intracranial Aneurysm Model

Diana Pinho, David Bento, João Ribeiro, Rui Lima and Mário Vaz

Abstract The purpose of this paper is to develop a system able to study experimentally the displacement field of an in vitro intracranial aneurysm. Origin and growth of aneurysms is the result of a complex interaction between biological processes in the arterial wall and the involved hemodynamic phenomena's. Once the aneurysm forms, the repetitive pressure and shear stresses exerted by the blood flow on the debilitated arterial wall can cause a gradual expansion. One promising method to evaluate and measure this expansion is to use optical field experimental techniques, such as interferometry. In this work the Electronic Speckle Pattern Interferometry was used to evaluate the deformation occurred on an intracranial aneurysm model fabricated in polydimensiloxane (PDMS) by using a 3D printer combined with a soft lithography technique.

Keywords Aneurysms · Displacement field · Electronic speckle pattern interferometry · 3D printer · In Vitro models

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1 Introduction

A cerebral aneurysm or intracranial aneurysm (IA) is a weak bulging spot on the wall of a brain artery very much like a thin balloon or weak spot on an inner tube. Over time, the blood flow by applying pressure against the thinned wall of the vessel artery leads to the appearance of aneurysms. This pressure may promote the rupture of the aneurysm and consequently the blood tends to flow to the surroundings outside the artery. It is worth mentioning that the rupture of a brain aneurysm most often requires advanced surgical treatment [1].

It is well known that blood flow behaviour in microcirculation depends on several combined effects such as cell deformability, flow shear rates and geometry of the microvessel, although still no consensus about the reasons for creation and rupture of aneurysms. Hence, a better understanding of the relationship between the pathophysiological aspects of an aneurysm and its arterial geometry or local hemodynamics is critical to better understand aneurysm growth, predict the risk of regrowth after treatment, and improve endovascular treatments. In order to investigate the hemodynamics in blood arteries, some mathematical and experimental studies have been performed over the years. Nonetheless, in vitro experiments have been conducted only for flows in simple geometries such as straight bifurcation using glass pipes or acrylic pipes [2], glass capillaries [3, 4] and more recently in polydimensiloxane (PDMS) microchannels [5–8].

A promising approach to understand the mechanical behavior of aneurysms is the global measurement of deformation using experimental field optical techniques. These optical techniques provide the accurate measurement of displacement and strain fields of the global deformation occurred on the aneurysm. The experimental field optical techniques can be classified in interferometric, photoelastic and Digital Image Correlation (DIC) [9]. The interferometric techniques are based on the interferometry phenomenon of light and use of a coherent light (laser), and the most common are the holography, the Moiré Interferometry and the Speckle methods [10]. The photoelastic methods use the optical properties (birefringence) of certain materials where when a ray of light passing through these materials experiences two refractive indices [11]. The DIC technique is based on the comparison of two images acquired at different states, i. e., before and after the deformation. By using this technique the object is illuminated by a non coherent light and the intensity patterns result of the surface texture [12]. In this work we have decided to measure the aneurysm deformation by using ESPI mainly because this technique enables a rapid and accurate determination of out-of-plane displacement field which is a predominant component of the displacement occurred in current study.

Recently, several numerical hemodynamics studies have been reported [2, 13] in order to better understand the creation and rupture of a cerebral aneurysm. Other studies have used a soft lithography method to manufacture in PDMS carotid arteries having an aneurysm with a thick wall [14, 15]. However, experimental analysis of in vitro cerebral aneurysms with geometries close to in vivo ones has not

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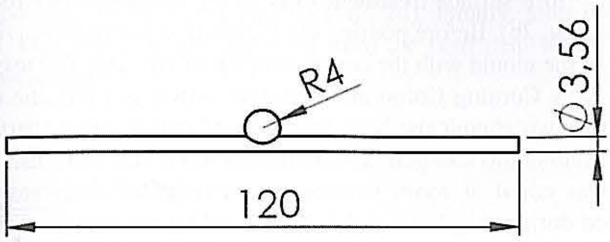


Fig. 1 Geometry and dimensions (mm), of the aneurysm model

been reported yet. This is mainly because it is extremely difficult to fabricate three-dimensional geometry models with thin walls.

The objective of this paper is to develop a realistic three-dimensional system able to obtain measurements of the expansion and pressure around the wall of an intracranial aneurysm. The experimental measurements are made using a Speckle method, more precisely an Electronic Speckle Pattern Interferometry (ESPI). This method uses a surface roughness illuminated by a laser beam, which generates a pattern that could be used to measure an out-of-plane displacement field. The aneurysm model was fabricated in PDMS by using Acrylonitrile Butadiene Styrene (ABS) molds manufactured with a 3D printer.

2 Materials and Methods

2.1 Geometric Parameters

The geometry and dimensions of the aneurysm model were based in clinical data for a common saccular intracranial aneurysm [16] and drawn in the Solidworks® CAD software. This geometry was used to produce the aneurysm model in PDMS for the experimental tests. In Fig. 1 it is represented the geometry and dimensions of the used aneurysm model.

2.2 Fabrication of the Aneurysm Model

The model of aneurysm has been produced in PDMS. This material is biocompatible and its elastic behavior is similar to the arteries [17]. To obtain the aneurysm model seen in Fig. 2e it was necessary to develop and elaborate a special mould with the same geometry and dimensions of the model. The mould was fabricated in ABS material using a Solidoodle® 3D Printer. In Fig. 2a it is possible to observe the mould and core used to obtain the PDMS aneurysm model and a detail of the 3D printer used for this study. The moulds and cores obtained from the 3D Printer were firstly subjected to a surface treatment to decrease the superficial roughness with acetone vapor (Fig. 2b). Before pouring the PDMS into the mould cavity, was made the assembly of the mould with the core (see detail of Fig. 2b). The used PDMS was Sylgard 184, Dow Corning Corporation product, which is a silicone elastomer kit. The kit contains two chemicals: base (part A) and curing agent (part B), that was mixed in 10:1 mass ratio and poured onto master mold in a Petri dish (see Fig. 2c). The PDMS was cured at room temperature in order to completely release the bubbles formed during the plinth of the PDMS and by the contact with the material of the mould and core. After a complete cure (42 h) of the PDMS the materials were

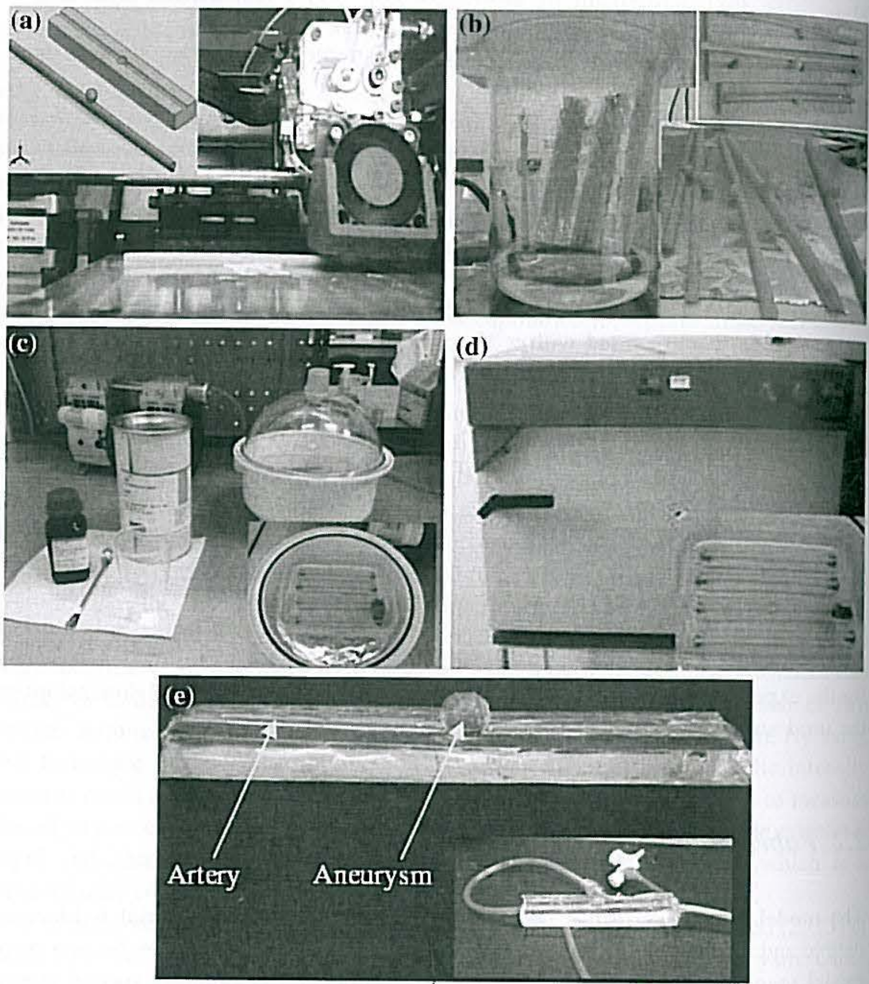


Fig. 2 Main steps of the fabrication procedure: **a** printing the geometries in ABS by means a 3D printer; **b** surface treatment with acetone vapors; **c** deposition of the polymer PDMS over the molds to obtain the channel; **d** curing the polymer at room temperature for 42 h and more at 80 °C for 30 min; **f** three-dimensional PDMS channel with the input/output connections

placed into the oven at 80 °C for 30 min (Fig. 2d). Finally, after the molds have cooled down, they were cut and taken off from the petri dish where the inlet and outlet holes were made.

2.3 Experimental Set-up

The experimental method used to obtain the measurement of displacement field on the PDMS aneurysm model was the ESPI. In this analysis the deformation occurred mainly on out-of-plane direction as the implemented ESPI set-up allows the measurement in this direction. To achieve this step, the experimental setup was coupled with an accurate image processing tool and designed to cancel rigid body motion only obtaining the above mentioned. The optical set-up used to measure out-of-plane displacement fields with ESPI are schematically represented in Fig. 3. In this case, the laser beam is splitted in two, one being the object beam and used to illuminate the object and the other being the reference beam. This combination generates a sensibility vector normal to the object surface. The mirror mounted on a piezoelectric transducer is used to implement the phase stepping technique, which in combination with image processing algorithms allows the calculation of the spatial phase distribution. The light source used was a 2 W laser from COHERENT (Verdi) with a radiation wave length of 514 nm.

To calculate the displacement field eight images were recorded at different phase shift, being half of them token before and the remaining after the injection of the glycerin.

The PDMS aneurysm model was fixed on the optical table and was pumped glycerin by means of a syringe pump with a flow rate of 250 μl/min. Figure 4 shows the aneurysm model placed in the out-of-plane displacement set-up.

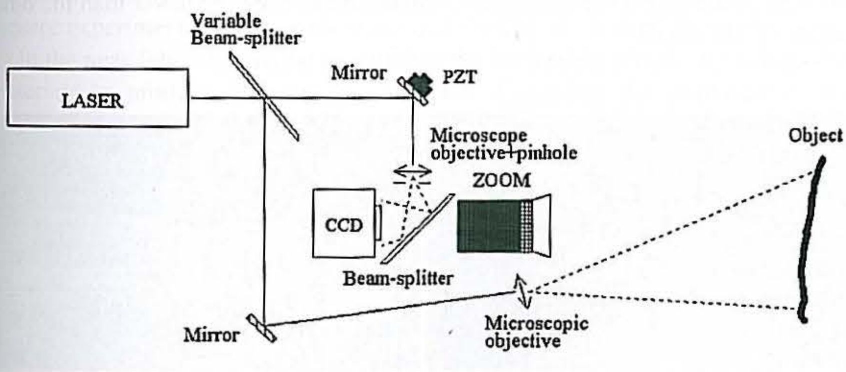


Fig. 3 ESPI set-up to measure out-of-plane displacement fields [18]

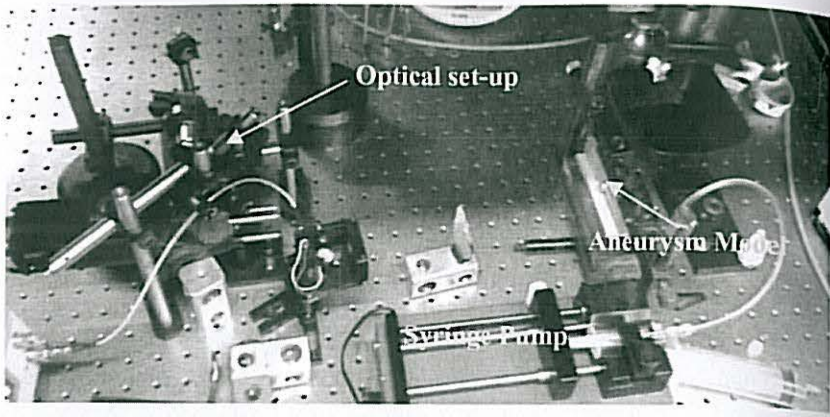


Fig. 4 PDMS aneurysm model in an out-of-plane displacement set-up

3 Results and Discussion

Using the ESPI the displacement field is calculated by subtracting the speckle phase maps obtained before and after the fluid flow. The discontinuities in Fig. 5a are due to the phase calculation algorithm and can be removed by phase unwrapping. Different solutions are available for this purpose according to the data spatial noise [19]. The results presentation could be improved using a pseudo color presentation where the displacement intensity is codified according to a color, see Fig. 5b.

A more understandable way to present the information is by showing a three-dimensional representation of displacement field. Figure 6 represents the displacement field measured with ESPI. Analyzing the obtained preliminary results it is observe that the maximum displacement has occurred on the aneurysm region and on the inlet of the artery. This phenomenon could be explained by two possible reasons: the pressure is higher in both aneurysm region and artery inlet; the wall thickness in the regions of the highest displacements could be lower than the other regions of the model.

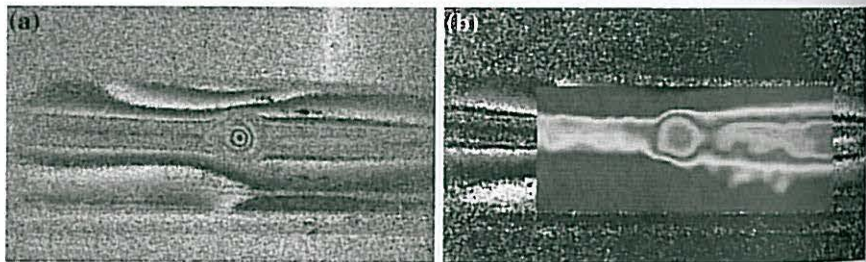
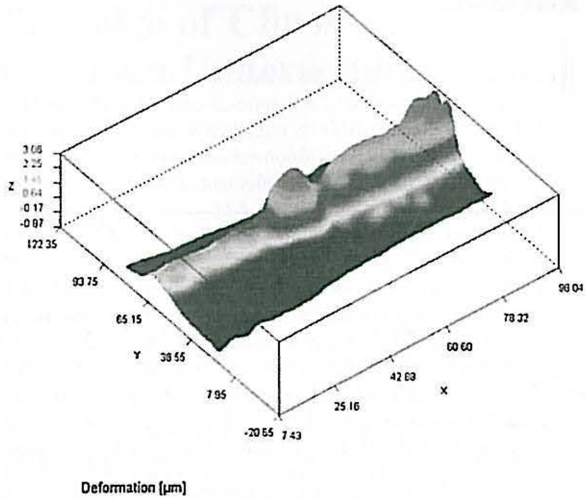


Fig. 5 a Phase map and b Unwrapped phase map of displacement field. The flow direction is from *right* (inlet) to *left* (outlet)

Fig. 6 Out-of-plane displacement field measured on PDMS aneurysm model with ESPI



4 Conclusions

The fabrication methodology used to obtain an aneurysm model has allowed to achieve an in vitro model with a geometry and dimensions very similar to a realistic in vivo aneurysm. However, the demolding process was extremely laborious and consequently some parameters like wall thickness and superficial roughness were difficult to control. The roughness of the moulds and cores can influence the velocity and pressure inside the model however the tested surface treatment with acetone vapors may be a good solution to eliminate this influence.

The optical technique of ESPI proved to be well adapted for displacement field measurement on PDMS materials. The results show that this technique correlates well in the displacements when high spatial resolution is used, allowing extracting the information for the applied deformation. A study to compare in more detail the present experimental results with numerical simulations is currently under way.

In the near future we intend to optimize the fabrication process by using others materials to produce the moulds and cores. Regarding the displacement field measurements we plan to obtain more accurate results and out-of-plane measurements by using other techniques such as Digital Image Correlation. Experiments at different and higher flow rates are also one of the futures goals.

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Paulo Flores · Fernando Viadero *Editors*

New Trends in Mechanism and Machine Science

From Fundamentals to Industrial Applications

This volume consists of the Proceedings of the 5th European Conference on Mechanisms Science (EUCOMES), that was held in Guimarães, Portugal, from September 16–19, 2014. The EUCOMES is the main forum for the European community working in Mechanisms and Machine Science.

This work presents the most recent research in the mechanism and machine science field and its applications. The topics covered include: theoretical kinematics, computational kinematics, mechanism design, experimental mechanics, mechanics of robots, dynamics of machinery, dynamics of multi-body systems, control issues of mechanical systems, mechanisms for biomechanics, novel designs, mechanical transmissions, linkages and manipulators, micro-mechanisms, teaching methods, history of mechanism science and industrial and non-industrial applications.

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