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Analysis of the structural behavior of a membrane using digital image processing

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ABSTRACT

This article presents a methodology for the experimental analysis of thin membranes using digital image processing techniques. The methodology is particularly suitable for structures that cannot be monitored using conventional systems, particularly those systems that involve contact with the structure. This methodology consists of a computer vision system that integrates the digital image acquisition and processing techniques on-line using special programming routines. Because the membrane analyzed is very thin and displays large displacements/strains, the use of any conventional sensor based on contact with the structure would not be possible. The methodology permits the measurement of large displacements at several points of the membrane simultaneously, thus enabling the acquisition of the global displacement field. The accuracy of the acquired displacement field is a function of the number of cameras and measured points. The second step is to estimate the strains and stresses on the membrane from the measured displacements. The basic idea of the methodology is to generate global two-dimensional functions that describe the strains and stresses at any point of the membrane. Two constitutive models are considered in the analysis: the Hookean and the neo-Hookean models. Favorable comparisons between the experimental and numerical results attest to the accuracy of the proposed experimental procedure, which can be used for both artificial and natural membranes.

1. Introduction

The analysis of natural membranes, such as biological membranes, and artificial membranes made of polymeric materials is an important research area in applied mechanics. Currently, elastic membranes are widely used in many engineering areas, such as aerospace [1–3], structural [4–8] and biomedical engineering [9,10], biomechanics [11–14] and in the development of sensors and actuators [15,16]. A detailed review of the membrane applications, theory and constitutive models can be found in [17–19]. The main reason for this wide range of use is that the membranes lead to lightweight and flexible structures. However, under the action of external loads, they may display large strains with small applied stresses and exhibit both geometric and material nonlinearities. Excessive stretch may cause rupture and tearing of the membrane.

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Therefore, accurate characterization through experimental techniques and the definition of reliable constitutive models that can describe their behavior in a given deformation range is essential to ensure the safety of the structure. Therefore, before any practical use, a constitutive model must be identified and validated. In general, uniaxial or biaxial mechanical tests are used to estimate the constitutive model parameters. Thus, the coupling of numerical simulation with experiments is essential.

For example, Przybylo and Arruda [20] conducted an experimental investigation and the numerical modeling of vinyl elastomers in large, non-homogeneous deformation states. The Arruda and Boyce, Yeoh and Ogden hyperelastic constitutive models were used to simulate the membrane behavior using a single uniaxial compression test. Rachik et al. [21] investigated the biaxial rheological behavior of a circular membrane using a bubble-inflation-technique. The inflation of the circular membrane was recorded using a CCD video camera and the blowing pressure using a pressure sensor. Sasso et al. [22] characterized the behavior of a hyperelastic rubber-like material using biaxial and uniaxial stretching tests based on optical methods. Recently, Selvadurai [23] examined the problem of the fluid pressure loading of a hyperelastic membrane made of a natural gum rubber. The results of the deflected profiles together with the computational modeling of the experiments were used to identify the range of applicability for several forms of strain energy functions for hyperelastic materials.

The mechanical properties of soft tissues are crucial in the areas of biomechanics, rehabilitation engineering, and surgical simulation. The validation of in vivo constitutive models remains challenging and often requires the use of non-invasive imaging coupled with numerical techniques. Wineman et al. [24] advocated the use of membrane inflation for the mechanical characterization of soft tissue. Hsu et al. [25] proposed a video-based experimental system for studying axisymmetrically inflated biomembranes. Data from tests on rubber membranes and fusiform aneurysms illustrated the utility of the experimental system. A review of the application of biaxial testing techniques to soft planar tissues and their relationship to relevant modern biomechanical constitutive theories was published by Sacks [26].

The experimental analysis related to structural behavior, such as elastic membranes using conventional sensors, is not viable because the introduction of these sensors' mass would completely affect the response of the structure. For this reason, there is a growing interest in the development of alternative experimental displacement measurement techniques without contact with the structure, such as the use of imaging with a computer vision system as a movement sensor, as shown in Refs. [27–35]. There are also interferometry techniques, such as speckle interferometry, speckle photography and hologram interferometry [36–42].

The aim of this work is to propose an alternative experimental methodology, which enables the measurement of displacements without requiring contact with the structure, in this case a hyperelastic membrane, using digital image acquisition and processing. Subsequently, the strain and stress field of the membrane can be estimated, and consequently, an appropriate constitutive model and the related parameters can be chosen. Thus, two methodologies have been developed in this work. The first methodology is experimental and is based on advanced image processing techniques, which can be applied to both full- and small-scale models. The second methodology aims to estimate the strains and stresses in the structures from the measurements obtained using the computer vision system. The basic idea of the methodology is to generate global two-dimensional functions that describe the strains and stresses at any point of the membrane. This is particularly advantageous in the analysis of new hyperelastic materials and biomaterials. Most constitutive models for these materials require the definition of several materials constants which are difficult to obtain using traditional uni- or bidimensional tests. By obtaining a detailed two-dimensional displacement field, any set of constants can be easily estimated by minimization procedures. However, the main advantage of this methodology is its application in non-invasive experiments to examine structures undergoing large deformations, such as in-vivo measurements and in-situ measurements in hazardous environments.

2. Experimental methodology

The experimental methodology proposed in this work consists of the following steps:

(i) Image capture: The image is acquired by an analog video camera with $\frac{1}{4}$-in NTSC and CCD, containing 811 (horizontal) $\times$ 508 (vertical) CCD pixels. The camera has a scanning system of 525 lines with 60 photos/s, 470-TVL resolution (TV lines), an electronic shutter with a speed of 1/120.000 s, manual and automatic focus, and a Cannon lens with a 22 $\times$ optical zoom and a focal distance ranging from 3.7 to 85.1 mm.

(ii) Digitalization: The analog images captured by the video camera are converted into digital images using a monochromatic (PCI – 1409/National Instruments) digitalizing (frame grabber) board inserted in the microcomputer.

(iii) Acquisition and processing of the digital images: This step aims to improve the quality of and highlight aspects of interest in the digital image.

(iv) Calibration: Using the known coordinates of the points of interest (x,y,z) in a reference surface and their image coordinates (u,v), obtain the transformation matrix that correlates these two sets of coordinates.

(v) Reconstruction: This step consists of obtaining the actual position of the points of interest and computing the displacements without making contact with the structure.

From these steps, a computational vision system based on the programming language LABVIEW, which handles the acquisition and processing of the digital image in real time, was developed. The program is named Image-Sensor Software