DEFORMATION MEASUREMENT AND ANALYSIS OF INFLATED AIR-SPRING SHELL USING STEREO-CORRELATION TECHNIQUE

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Introduction

The measurement of displacements and deformations has always been an important topic in the evaluation of material properties. In the last decade, a non-contact optical technique, digital image correlation (DIC), is developed for the displacement determination of the object under loading. The three-dimensional (3-D) displacement measurement requires the use of at least two synchronized cameras acquiring images of the loaded specimen from different viewing angles. By determining corresponding image points accross views from the different cameras and tracking their movement throughout the loading cycle, the shape and deformation can be reconstructed by the triangulation.

Several works have been done on 3-D displacement and deformation measurement using two cameras or single camera (Luo et al., 1998; Garcia et al., 2001, 2002). The stereocorrelation was applied by Luo et al. (1998) to the measurement of curved surfaces. The stereovision technique has been used to measure 3-D strains of formed sheet metal parts and of inflated elastomeric membranes (Garcia et al., 2002). The ability of a DIC technique to capture the heterogenous deformation fields appearing during compression of ultra-light open-cell foams is described in paper of Wang and Cuitino (2002).

Camera calibration is a fundamental step in 3-D computer vision, specially when the metric informations are required for applications involving accurate dimensional measurements. Camera calibration is the process of determining the internal camera geometric and optical characteristics (intrinsic parameters) and the 3-D position and orientation of the camera frame relative to a certain world coordinate system (extrinsic parameters) and the determination of the geometry of the stereo rig (the relative position and orientation of the two cameras).

Next task is to determine the corresponding points between pairs of stereo-images (stereo-matching) and retrieval of the corresponding points in the series of images taken by the left camera (or the right one) at different stages of loading (temporal matching). The

matching techniques and corresponding algorithms can be divided into major categories: area-based, feature-based and hybrid (Cardenas-Garcia et al., 1995). Area-based algorithms which use image intensity level distribution to find the best match between a pair of images are comprehesively evolved in works of Garcia and Orteu (2001, 2002).

The last step is the triangulation – the determination of the 3-D coordinates of the specimen surface from the disparity value of surface points at different loading steps and then calculation of the displacements and the deformation. In this paper, the 3-D displacements and deformations of inflated cylindrical shell of air-spring are measured accurately by the application of the stereo-correlation technique.

In this paper, the stereo-correlation technique in stereo vision is used to measure the 3-D displacements and deformations of inflated cylindrical shell part of air-spring made of cord-rubber composite. The mechanical tests using two cameras have been done in inflated cylindrical shell of air-spring at the different loadings. Using digital image correlation the 3-D coordinate of points in the central part of air-spring shell are obtained at different stages of loadings. By the use of the nonlinear optimization technique, the equation of cylindrical surface of air-spring shell is solved to obtain a set of parameters, the direction cosine of the centerline of the cylinder, the point of intersection of the centerline of the cylinder with the XZ-plane, and the radius of the cylinder. The computed radius of the cylinder is compared to the measured value to evaluate the measurement error.

As known in our publications the strain energy function is expressed in terms of tensorial invariants with regard to the assumed material symmetry. The material paremeters of strain energy function of the hyperelastic orthotropic material are fitted to the experimental results by the nonlinear least squares method. The deformation of air-spring is calculated by solving the system of five first-order ordinary differential equations with the material constitutive law and proper boundary conditions.

Experimental set-up

In our experiments the serial left and right images at different stages of loading are recognized by two cameras.The black air-spring sheathing was marked with the white spray paint which resulted in a fine textured random pattern (Fig. 1). Schematic diagram of Camera model (Fig. 2) is used to acquire digitized images of the surface of air-spring shell before and after deformation at different stages of loading and unloading.

Fig. 1. The air-spring is pressurized

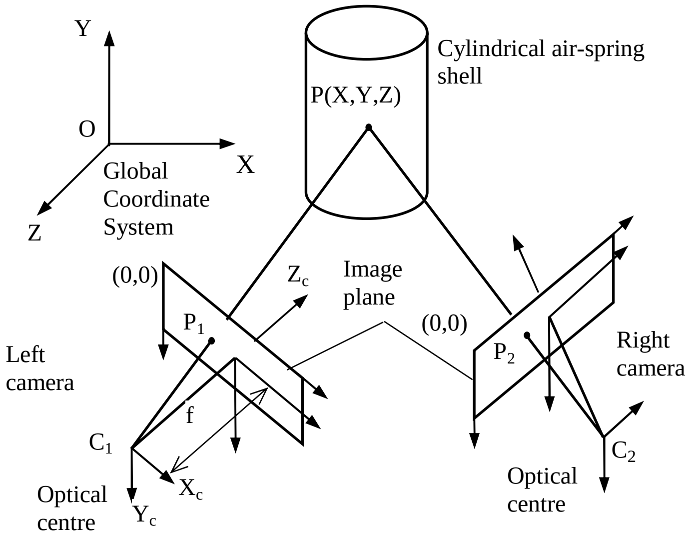

Fig. 2. Schematic diagram of Camera model

The air-spring was loaded and unloaded gradually by pressurized air by step 0.02 MPa in the range 0–0.3 MPa and then by step 0.05 MPa up to 0.6 MPa to guarantee a small deformation (<20%) between each image of the sequence. Images of the size of 1280x960 pixels were recorded by two digital cameras Minolta mounted on a special support. The axial force and the inner pressure were measured and stored at every stage of loading.

Camera calibration

Camera calibration toolbox for Matlab which is developed by Bouguet (2004) was used in our work. Calibrating stereo rig is dealt with by calibrating each camera independently and then applying geometric transformation of the external parameters to determine the geometry of the stereo rig. The checkerboard pattern with 10 mm squares is used on the calibration. All the calibration images used in one of our experiments are showed in Fig. 3. Fig. 4 illustrates an image after corner extraction. The result of calibration is:

Intrinsic parameters
Focal Length: fc_left = [2798.67375 2807.58737]
fc_right = [2986.40129 2994.80468]
Principal point: cc_left = [670.04807 585.78871]
cc_right = [685.64123 605.86915]
Distortion: kc_left = [-0.00395 3.24668 0.01156 0.00749 0.00000]
kc_right = [0.07555 1.77120 0.01461 0.01260 0.00000]
Extrinsic parameters (position of right camera wrt left camera):
Rotation vector: om = [0.01478 0.47729 0.03584]
Translation vector: T = [-345.41229 -5.64866 123.96245]

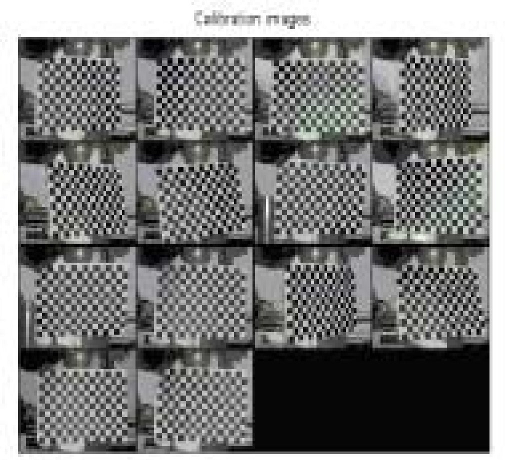

Fig. 3

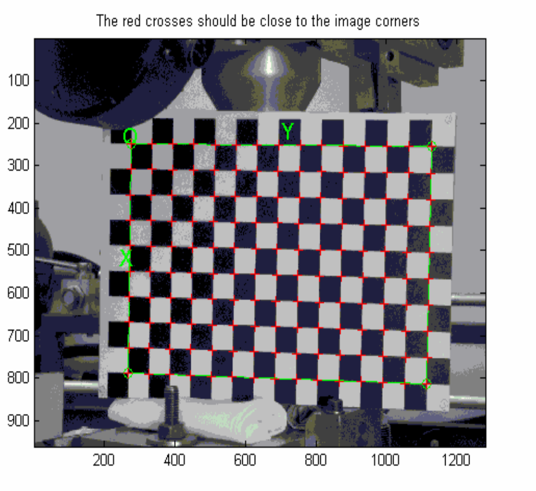

Fig. 4

Stereo and temporal matching

Area-based algorithm uses image level disrtribution information directly to find the best match between a pair of images. The area-based method is used to find the correspondence between two stereo images. In the stereo-matching problem we have been done temporal-matching the two images taken by the left camera (or the right one) before and after deformation to compute the 3-D displacement corresponding to each image point. At the same time we used stereo-matching for the pair of stereo images at the same stage of loading. The area-based correlation function was calculated for a grid of 5x5 pixel in the central part of every image. The images were not rectified and the epipolar line was calculated for every point of interest. The disparity for every point was calculated and the spatial coordinates of

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surface points vere determined (Fig. 5). The computed mean radia of air-spring shell at loaded and unloaded stages are shown in Fig. 6.

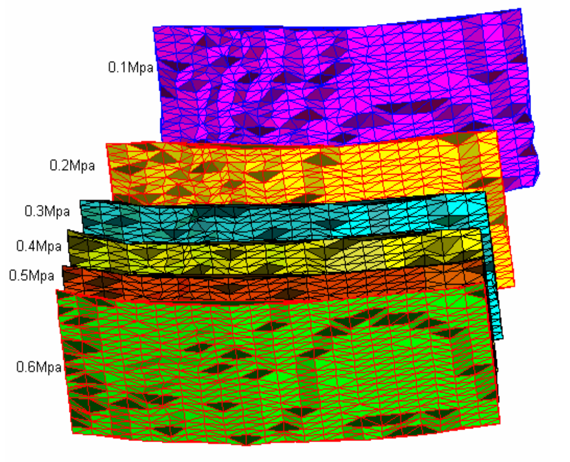

Fig.5. The 3-D displacements of air-spring

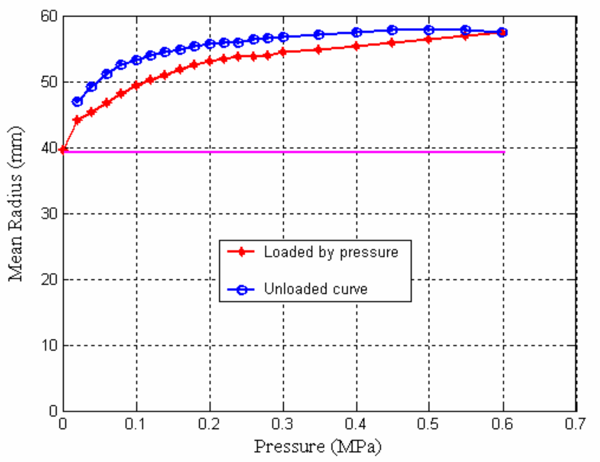

Fig. 6. The mean computed radia

Deformation analysis of inflated air-spring shell

In this section the parameters of strain energy function are fitted to the experimental results by the nonlinear least squares method. The resulting parameters were k_1=31.63MPa and k_2 = -14.42.

The deformation field is then calculated by solving the system of five first-order ordinary differential equations with the material constitutive law and proper boundary conditions (Marvalová & Nam, 2003). The results are at the following figures where calculated stretches and deformed profiles of membrane are compared with experimental ones.

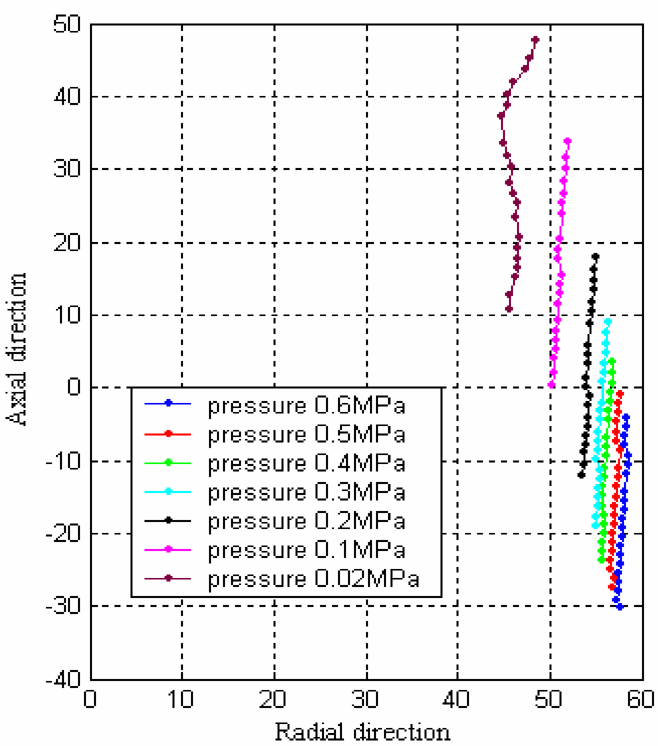

Fig.7. The deformed profiles of central part of inflated air-spring shell

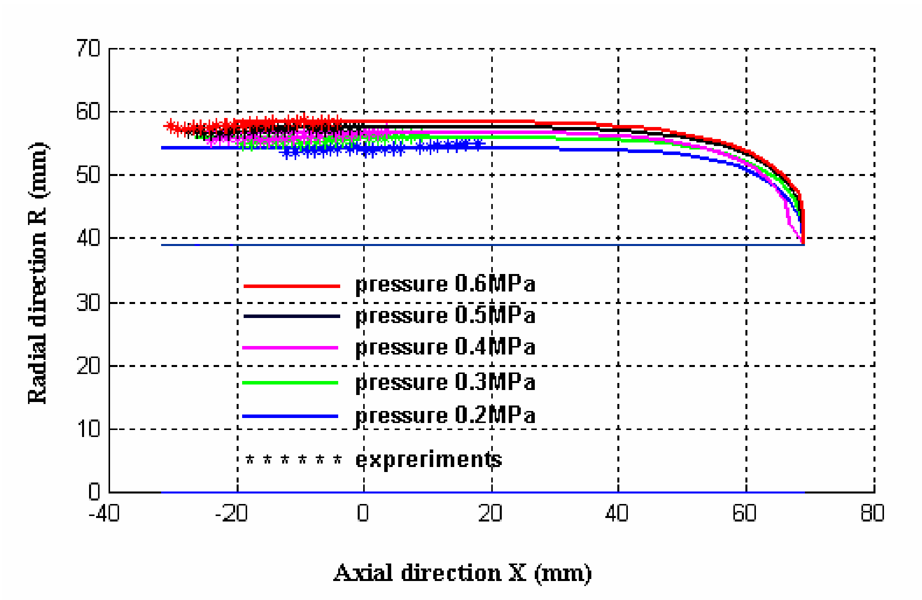

Fig. 8. Deformed profiles of inflated cylindrical air-spring shell

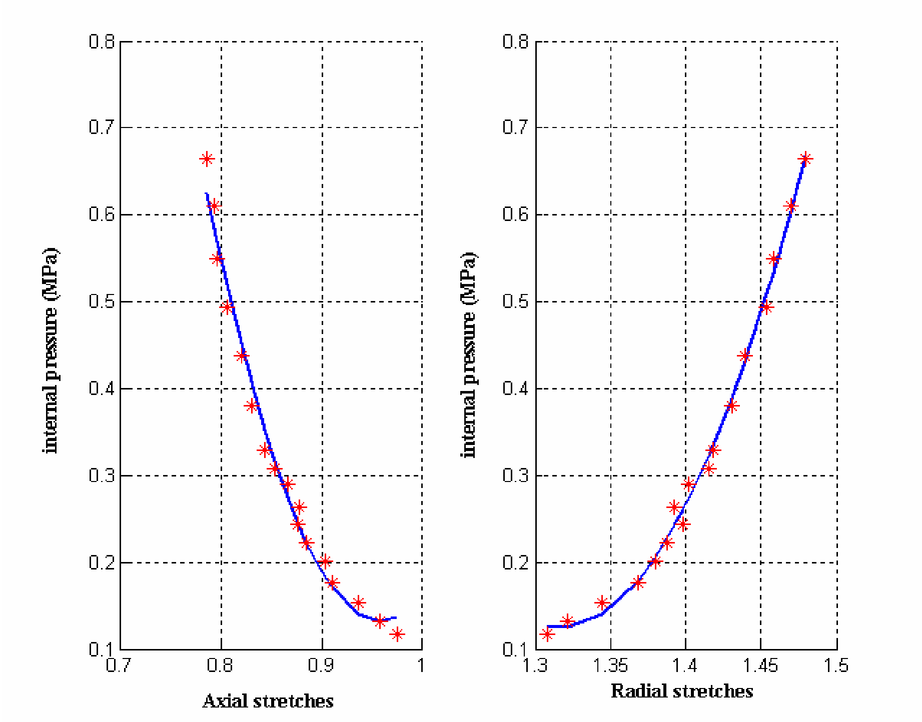

Fig. 9. Axial and radial stretches of inflated air-spring shell

Conclusion

An experimental method using two digital cameras for 3-D displacement and deformation measurement is presented. The 3-D coordinate of points in the central part of air-spring shell are obtained at different stages of loading using digital image correlation. 3-D displacements and deformations of inflated cylindrical shell part of air-spring made of cord-rubber composite by the application of the stereo-correlation technique. The computed radius of the cylinder is compared to the measured value to evaluate the measurement error (maximal error is less than 1%). Results indicate that the stereo-correlation technique may accurately measure the curved surface in various curvatures. Hence, the analysis method presented in our study may be further applied to study other deformation problems. The

problem of the identification of the material parameters was solved. The deformations were determined by numerical solution the system of ordinary differential equations based on the membrane theory. The method will be used for the inverse identification of material parameters of the inflatable structures namely air-springs.

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ABSTRACT

The 3-D displacements of inflated cylindrical shell of air-spring made of cord-rubber composite are measured by the application of the stereo-correlation technique. The 3-D coordinates of points in the central part of air-spring shell are obtained at different stages of loading by the matching of a series of stereo images. By the use of the nonlinear optimization technique, the deformations of the air-spring shell are determined. The material parameters of strain energy function are identified. The deformations of inflated air-spring shell were determined by numerical solution the system of ordinary differential equations based on the membrane theory.