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Measurement of the Geometry of a Parachute Canopy using Image Correlation Photogrammetry

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The systematic application of a stereo-image based correlation photogrammetry technique was used to measure the geometry of a fully-inflated model parachute canopy. The laboratory scale experiments were conducted in a low-speed water tunnel at a freestream velocity of 0.2 m/s. The model canopy had a constructed diameter of 0.3 m, and was made from a single piece of fabric. A stochastic pattern of small markers was applied to the canopy surface to permit the use of a correlation-based processing scheme. Measurements of the flexible model canopy appeared to present reasonable values for the imaged portion of the canopy. The experiments have demonstrated that the correlation-based technique has the potential of providing quantitative data on the canopy surface geometry with acceptable uncertainties.

Nomenclature

D	=	canopy constructed diameter
D_p	=	canopy projected diameter
f	=	breathing frequency
r	=	parachute radius
St	=	Strouhal number
U	=	freestream velocity
x	=	axial coordinate
y	=	transverse coordinate
z	=	transverse coordinate

I. Introduction

ALTHOUGH drag and stability characteristics of various parachute systems have been examined thoroughly, the geometry of the surface of fully-inflated round parachute canopies has not been studied in detail previously. The three-dimensional surface of an inflated round parachute is an important parameter for design and performance analysis. However, the challenge in the modeling of such system is the flexible nature of the structure involved. The ability to describe quantitatively the canopy geometry as a three-dimensional surface has several applications: (a) it allows modal analysis of the canopy, and as a result, the effective fabric properties, (b) it can be used as an initial condition for Fluid-Structure Interaction (FSI) computations, and (c) it may be used for validation and verification of high-fidelity FSI simulations.

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Several recent computational studies have analyzed the parachute geometry and performance using coupled computational fluid dynamics and structural dynamics codes.[1,2,3] On the other hand, experimentally, the maximum dimensions of round parachute canopies have been determined from visual images recorded by ground-based or airborne cameras,[4,5] or 3-D laser scanning of sub-scale models.[6,7] Both Berndt[4] and Heinrich and Noreen[5] used high-speed movies to study the geometry of sub- and full-scale round parachute canopies. Very recently, Lee and Li[6] measured the time-averaged geometry of inflated model canopies using 3-D laser scanning technology. Along with their experimental technique, mathematical methods were developed to analyze the scanned data to determine the three-dimensional geometry, surface area, and volume of parafoils and round parachutes.

An alternative shape measurement technology consists of a combination of conventional photogrammetry technique with 3D digital image correlation methods.[8,9] In this technique, which is termed Image Correlation Photogrammetry (ICP), a stochastic pattern of markers with good contrast is applied to the measurement surface, which deforms along with the object. The deformation of the structure is recorded by the CCD cameras and evaluated using digital image processing. The initial image processing defines a set of unique correlation areas known as facets. The facets size is typically 5-25 pixels square across the entire imaging area; the center of each facet is a measurement point. These facets are then tracked in each successive image with sub-pixel accuracy. Using photogrammetric principals, the 3D coordinates of the surface can be calculated. It is to be noted that as long as the object remains within the field of view of the stereo camera pair, the relative position of all points at the center of subwindows within the imaged area can be tracked and local deformations can be computed.

In this paper, the systematic application of a stereo-image correlation photogrammetry technique to the measurement of the surface geometry of a fully-inflated parachute canopy model is described. First, a set of tests were performed to determine the various parameters and the uncertainties associated with this application, and then a time series of images were acquired for a model canopy in a water tunnel. In this manner, the structural dynamics of a fully-inflated round canopy was captured. From the data various properties of the model canopy were extracted.

II. Experimental Setup

The experiments were conducted in a water tunnel at a freestream velocity of $U = 0.20$ m/s. The water tunnel test section had a 0.6 m square cross-section and was 2.4 m long. The freestream turbulence at this velocity was less than 1%. Optical access was available through the transparent Lexan test-section walls. Figure 1 shows the inflated canopy in the water tunnel and the supporting hardware. The model parachute assembly was positioned in a horizontal orientation, and off-axis motion was restricted by a retentioning line along the canopy symmetry axis.

The constructed diameter of the model canopy was $D = 0.3$ m (1 foot) which results in a Reynolds number based on the freestream velocity of 6.1×10^4. The model canopy was made from a single piece of fabric to reduce the relative stiffness present in small-scale parachute models. The canopy was attached by 24 suspension lines to a stationary streamlined forebody. A stochastic pattern of markers with sizes corresponding to 3 to 5 pixels was applied to the canopy surface using spray paint. The random painted pattern (as shown in Fig. 1) did not appear to affect the model canopy's characteristics or breathing. Images of the pattern on the canopy surface were recorded by a stereo pair of CCD cameras (LaVision Image Pro X) with a 10 Hz frame rate at resolution of 1600 × 1200 pixel. Nikon 28 mm *f* 2.8 lenses were used for imaging. The model canopy surface was illuminated by a pair of flood lights placed near the tunnel test section. The recorded images were then processed using a commercial software suite (ARAMIS v6) system. For optimal results, 25 pixel square subwindows were used. The spatial resolution for the canopy model in the water tunnel, corresponding to 25 pixel squares, was 4.2 mm (= 0.16"). The minimum displacement sensitivity was less than 10 microns (~ one half of one thousands of an inch). The "average" coordinate of the center in each window with respect to a calibration plane was determined with sub-pixel accuracy. By processing all of the windows associated with the visible portions of the model, the three dimensional coordinates of a large number of "spots" on the canopy surface was determined. From the data, the three-dimensional geometry of the canopy surface was computed. The average uncertainty of the surface displacement is estimated to be ±1.4% of the imaged dimension. This estimate is based on the pixel count uncertainty, as well as the uncertainty of spatial system of camera and lens.

III. Verification

Three rigid objects consisting of a flat plate, a rectangular block, and a rigid canopy model, as shown in Fig. 2, were examined to assess the actual deviations involved with the measurements in the water using this system. The spatial resolution corresponding to 25 pixel squares was 3.72 mm (= 0.146"). The minimum displacement sensitivity for these cases was also less than 10 microns. The results of measurements carried out by the ARAMIS system are discussed below.

A. Flat Plate

Figure 3 presents the data for the flat plate in the water tunnel. The stereo image pair are shown in green color, and the computed surface geometry in grey. The computed shape is a flat rectangle, as expected. The distance between points A and B was computed to be 5.13" while the physical distance was measured to be 5.125" on the model. The calculated distance between points C and D was 6.86" in ARAMIS; the measured distance was 6.87". The differences between the physical measurement and the computed values are negligible for the case of the plate in the water tunnel.

B. Rectangular Block

The rectangular block has dimensions of 2.0" wide by 1.0" deep by 3.0" long. Figure 4 shows the computed data for the block. The distance for width, depth and length from the data were calculated to be 1.98", 0.97" and 2.99", respectively. The largest deviation of 3% was in the depth direction, and corresponds to 0.03". These deviations are relatively small, compared to the dimensions of the block.

C. Rigid Canopy

Figure 5 shows the images and the resulting geometry of the rigid canopy model. Clearly, the curvature of the model has been recognized by the ARAMIS system. The majority of the canopy model viewable by the camera pair was re-created by the ARAMIS system. A sufficient number of markers were required in order to avoid any “blank” areas, i.e. without any data. The subwindows where the correlation technique failed are denoted by the blank areas. The measured distance between points A and B was 2.00". The distance calculated between these points was 2.05". Similar to the other two cases, the deviation on the curved surface is small (50 thousands of an inch).

The ARAMIS system produces three-dimensional position of marked surfaces with uncertainties on the order of 50 thousands of an inch or less for the scales of ~ 4 - 5" studied in this set of experiments. Thus, this system can be used in a laboratory setting for the study of model canopy surfaces with reasonable accuracy. It is important to note that the calibration of the system is critical to the success of the measurements. Moreover, the use in a water tunnel with refractive index changes along the optical path requires special consideration. For example, in the current set of experiments the camera bar had to be parallel to the water tunnel wall to generate acceptable calibration and results.

IV. Results

Figure 6 shows the re-created surface of the flexible model canopy in the water tunnel. Measurements of the model canopy appear to present a reasonable geometry for the imaged portion of the canopy. Only a certain portion (about one third) of the entire canopy surface could be viewed at any time with the stereo camera pair. Data were also missing in the crevices between the gores. In order to “fill-in” the missing data in the crevices, interpolation of the adjacent points was used.

From the data, the dynamic displacement for an arbitrary point near the canopy skirt was computed. Figure 7 shows the displacement of a point marked by a dot on the intersection of the green lines in Fig. 6 for a period of 40 seconds. The displacement of the point in the x, y, and z directions are presented in Fig. 7. It should be noted that the canopy rotated somewhat during this period.

The spectral content of the z displacement for the point near the canopy skirt was obtained by applying the Fast Fourier Transform (FFT) to the data. The plot in Fig. 8 shows the frequency content of the z displacement data. The spectrum plot shows three major frequencies at f = 0.03, 0.13, and 0.58 Hz, respectively. These frequencies correspond approximately to the Strouhal numbers ($St \equiv f D_p/U$) of 0.033, 0.14, and 0.63. The first mode, which had a very low frequency and was believed to be noise, was ignored. The second mode corresponds to the helical shedding mode associated with axisymmetric bluff bodies, and a similar Strouhal number (0.16) was observed in previous studies of this canopy model.[10] The highest frequency mode with a Strouhal number of 0.63 is associated with the breathing of the canopy. This mode was observed at a Strouhal number of 0.55 in previous studies[10] examining the maximum projected diameter of the canopy.

The present data reveal a breathing frequency that is nearly 15% greater than the value reported by Johari and Desabrais.[10] To resolve whether this difference stems from the method for determining the frequency, a method for measuring the effective radius of the canopy was devised. This manner the effective radius should be comparable to the method used in Ref. 10 to estimate the canopy dynamics. The canopy effective radius was computed by fitting a circle to the edge of the re-created canopy surface. It is worth noting that data about one-third of the canopy was only available for the fitting. The spectral content of the computed effective radius shown in Fig. 9 was obtained by taking the FFT of the data. The spectrum shows a single dominant frequency at f = 0.6 Hz. This frequency which corresponds to a Strouhal number of 0.65 is very close to the 0.63 value obtained from the spectrum of zdisplacements. Thus, the present data provide a breathing mode with a Strouhal number in the range of 0.63 - 0.65. These value are about 15% greater than that reported in Ref. 10 for the same Canopy model.

The principal strain for the chosen point on the skirt of the canopy was computed, and further broken down to major and minor components. The former is the strain along the direction of deformation, and is shown in Fig. 10. This plot represents the major principal strain for a period of 40 seconds. The data show a very chaotic behavior with values ranging from -1% to 1%. The values of strain are negative during the first 10 s, and then oscillate about zero. The average value of major strain over this time period is 0.16%, which is indicated by the red line in Fig. 10.

V. Summary

The surface geometry of a fully inflated fabric canopy model was measured by the stereo-image based correlation photogrammetry technique. The experiments have demonstrated that this technique has the potential of providing quantitative data on the canopy surface geometry with acceptable uncertainties. In addition, the data also provide useful information on the dynamics of the canopy and structural parameters. Capturing the entire surface of canopy models with multiple cameras would greatly enhance the capability of this technique, and is recommended for future work.

Acknowledgement

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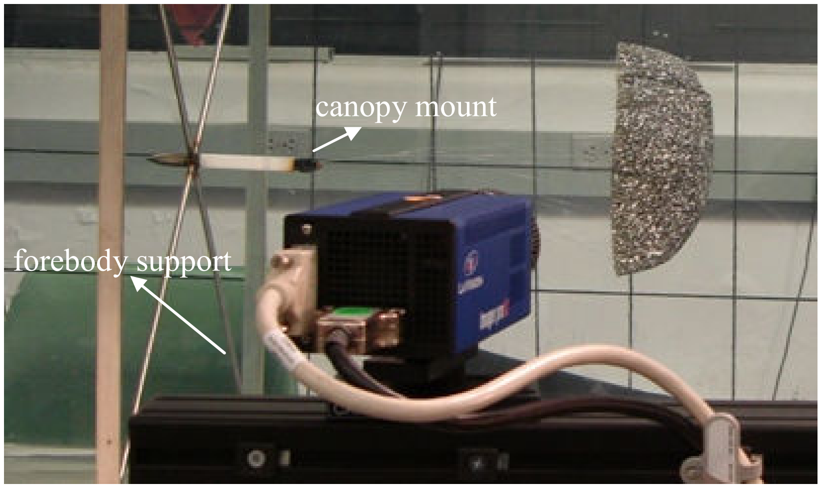

Figure 1. Forebody support structure and the canopy in the water tunnel.

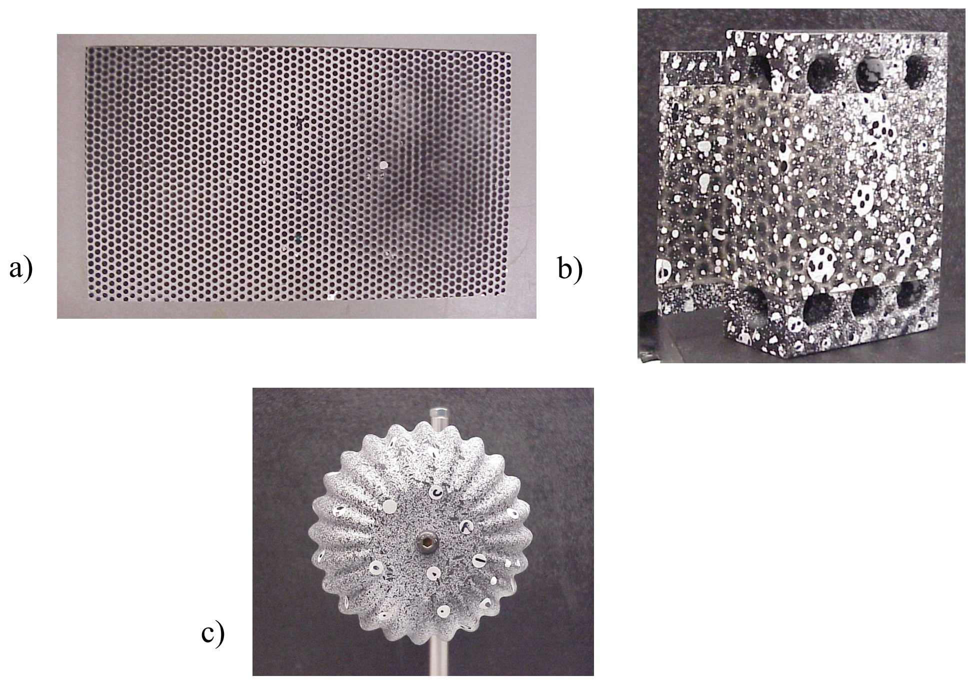

Figure 2. Rigid models used for verification: a) flat plate; b) block; and c) rigid canopy.

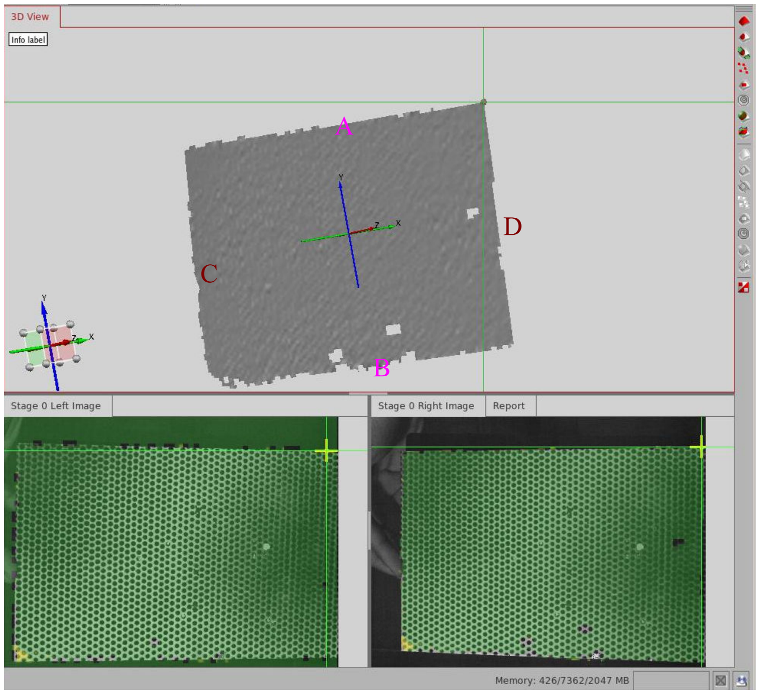

Figure 3. Stereo images and recreated surface of the flat plate.

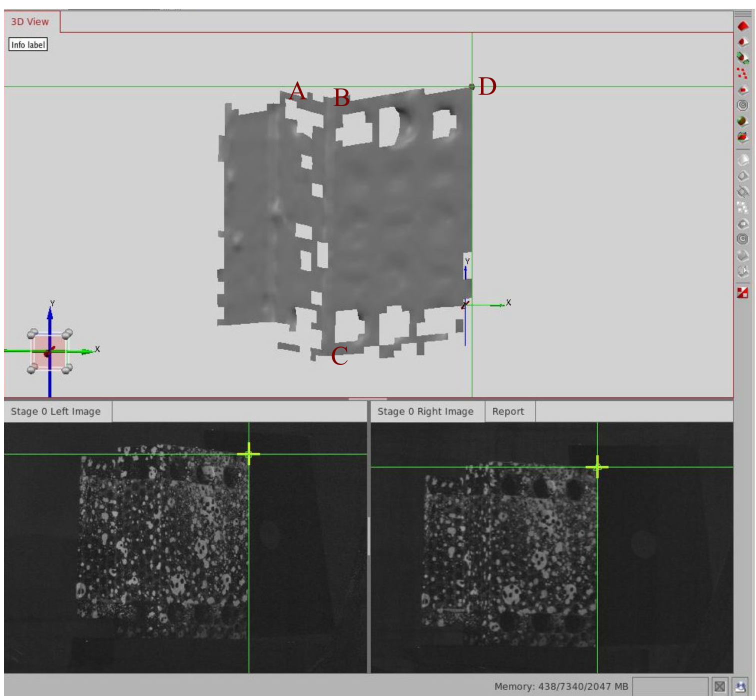

Figure 4. Stereo images and recreated surface of the block.

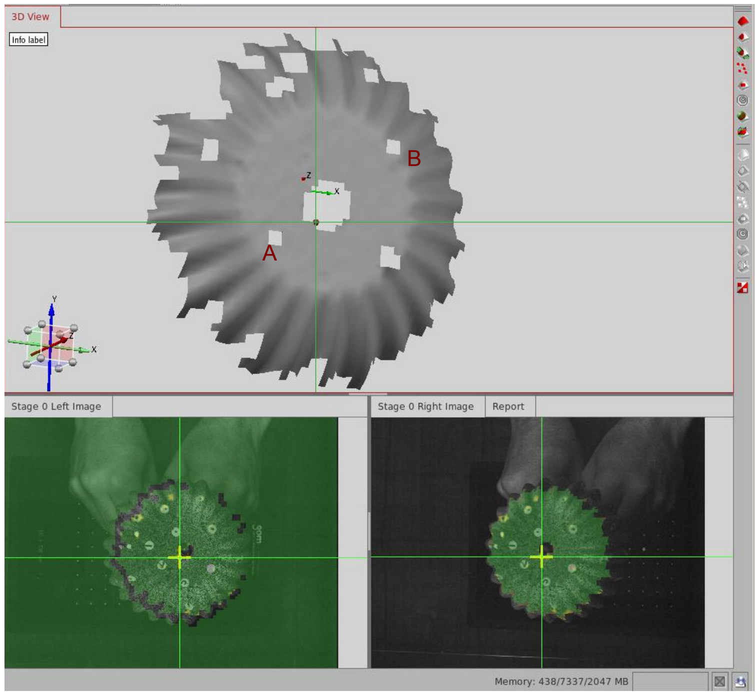

Figure 5. Stereo images and recreated surface of the rigid canopy model.

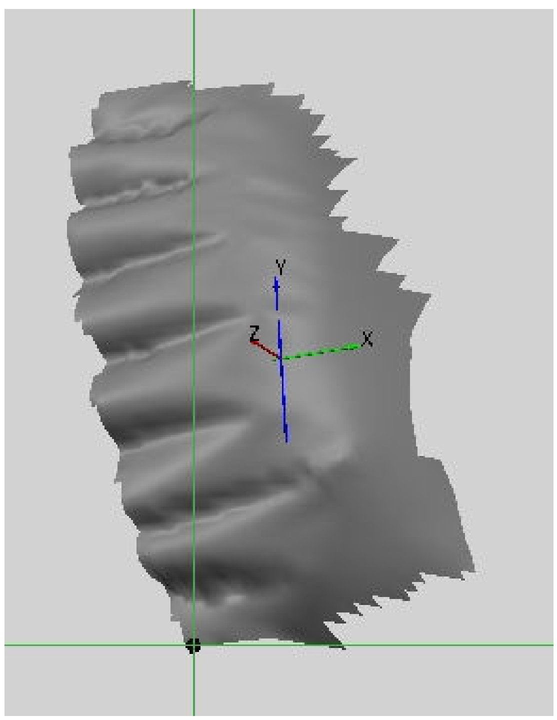

Figure 6. Recreated surface of the flexible canopy model in the water tunnel.

a)
b)
c)

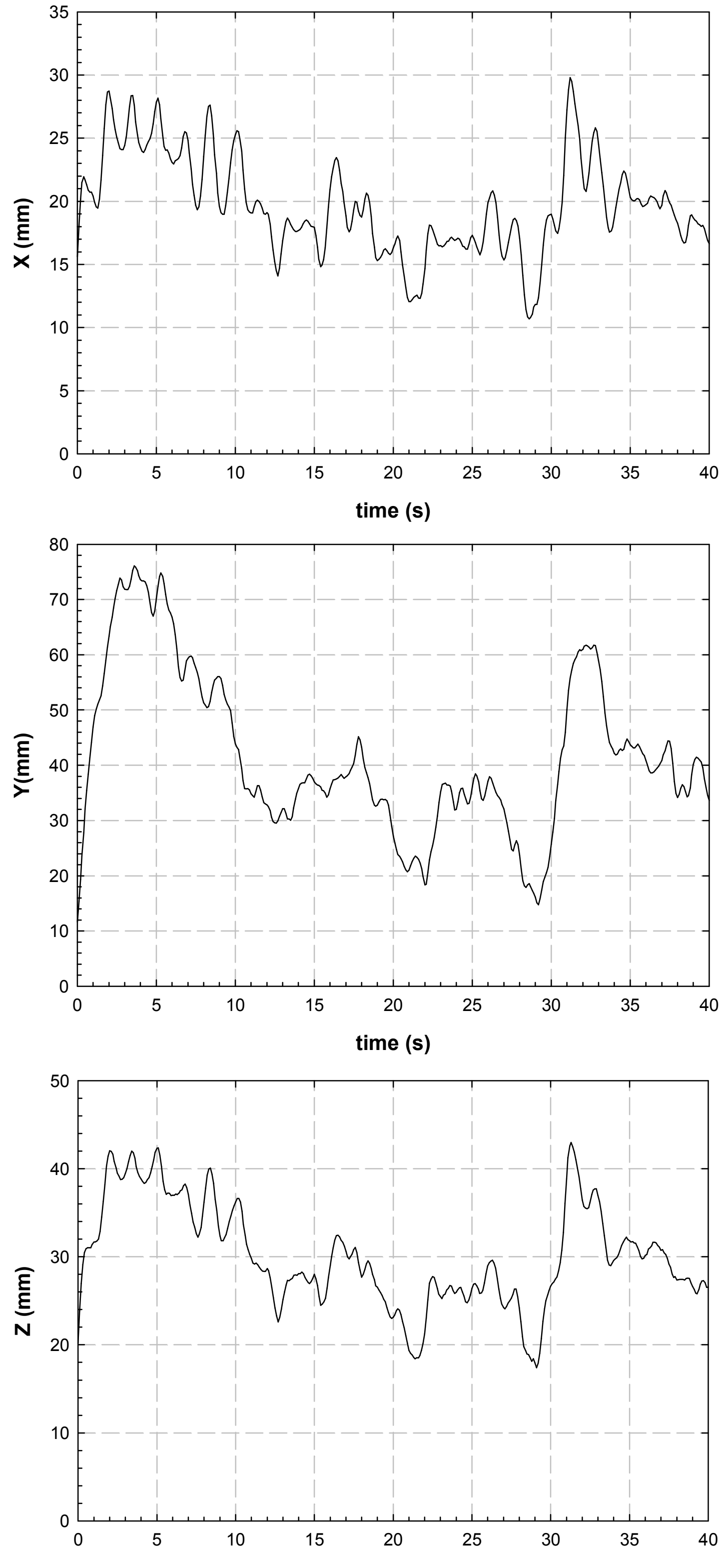

Figure 7. Time history of the displacement of an arbitrary point on the model canopy skirt; a) axial direction (x); b) transverse direction (y); c) transverse direction (*z*).

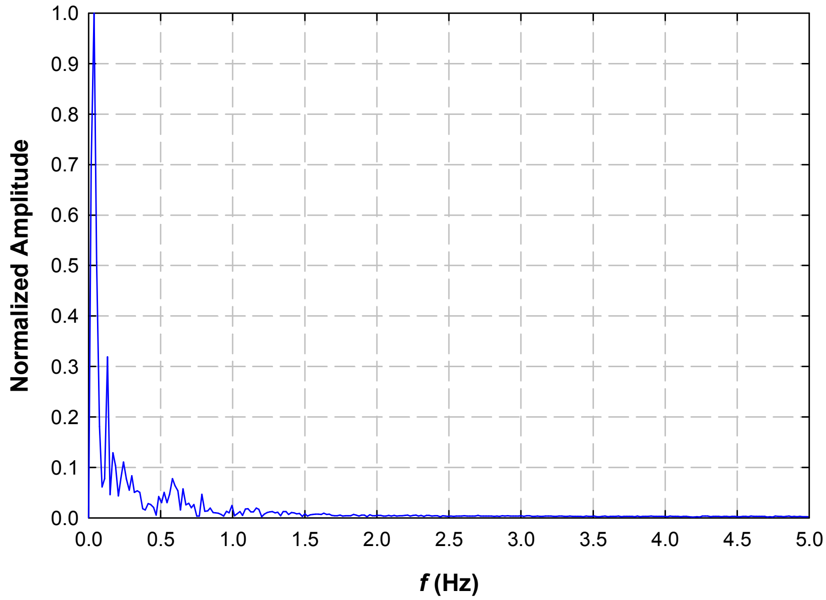

Figure 8. The FFT of z displacement.

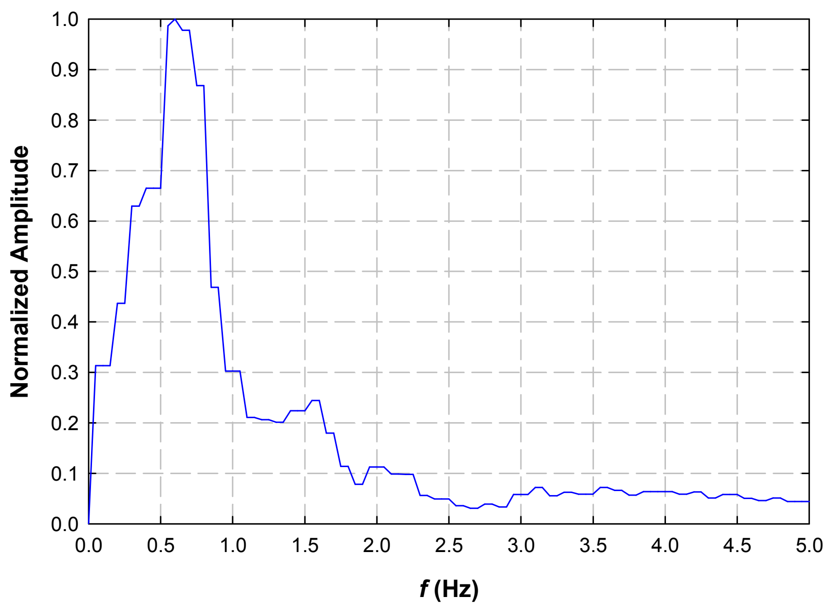

Figure 9. The FFT of computed canopy radius.

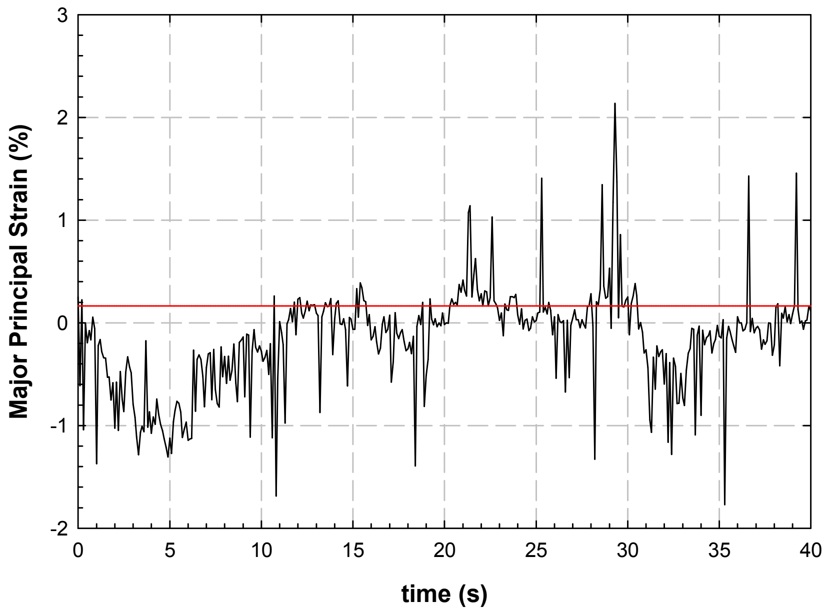

Figure 10. The major principal strain at the chosen point on the canopy model skirt.