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MEASURING THE DEFORMATION OF THE SUPER PRESSURE BALLOON USING THE SIMPLIFIED DIGITAL IMAGE CORRELATION METHOD †

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Abstract:

A super-pressure balloon (SPB) is a vehicle which can fly at a constant altitude for an extended period to perform scientific observations at a fraction of the satellite cost. The balloon is always pressurized to keep its volume constant, which suppresses buoyancy fluctuation due to the difference of internal gas temperature between day and night. We have been developing a lightweight, high strength balloon made of thin polyethylene films and diamond-shaped net with high tensile fibers. Although previous research shows that the tensile strength of the net meets the requirements as a strength member of the SP balloon, the net covering the SP balloons are sometimes broken at its inflation test. It is considered to be due to non-uniform expansion which causes stress concentration, however, there is no method to confirm this hypothesis. In this study, we have developed a simplified digital image correlation (SiDIC) method using the intersection detector, which allowed us to track the diamond-shaped weave of the net to measure the balloon deformation during the pressurization process. Digital image correlation (DIC)—an optical method to measure changes in images—usually requires black spots on the specimen for its analysis. However, such method is not suitable to study the shape of SP balloons, as ink spots on the thin film may affect its strength and weight properties. Thus, we developed this SiDIC approach, which overlays the intersection detector to the DIC. This made it possible for the program to track intersection points on the net without using the ink spots. First, this new method was tested using a rubber balloon covered by black patterns and a diamond-shape polymer net. A series of pictures of the balloon as inflated by air at a constant rate were taken and the deformation was measured using the DIC and SiDIC method to compare the results. From the results, the SiDIC almost agree with the result by the DIC method. The error between the DIC results and the real deformation were 87%, and the error between the SiDIC results were 84%. Next, to identify whether the DIC and SiDIC method can be used on the SPB, a rubber balloon covered just with a diamond- shape polymer net was used. In this test, the DIC method could not measure the deformation accurately and had an error of 56% between the real deformation, whereas the SiDIC

had an error of 83%. Therefore, the SiDIC method is suitable for monitoring the deformation of the SPB.

Keywords: Super-Pressure balloon, Stress concentration, Strain, Noncontact measurement, Digital Image Correlation, Large deformation

1. Introduction

A super-pressure balloon (SPB) is a vehicle that can fly at a constant altitude for an extended period to perform scientific observations at a fraction of the cost of using a satellite. The SPB is always pressurized to keep its volume constant, which suppresses buoyancy fluctuations due to the difference of internal gas temperature between day and night. A balloon with a maximum volume of 532,000 cubic meters developed by NASA was launched in New Zealand in March 2015, 2016, and has successfully flighted 33.5 km altitude for more than one month. In addition, GoogleX launched a communication balloon from 2014, updated the flight record in succession and succeeded in flight for 187 days [1-3]. We have been developing a lightweight, high strength SPB made of thin polyethylene films and diamond-shaped net with high tensile fibers. Although previous research shows that the tensile strength of the net meets the requirements of a strength member of the SPB, the nets covering the SPBs sometimes become damaged during the inflation test [4,5]. This may be due to non-uniform expansion which causes stress concentration, although no method exists to confirm this hypothesis [6-9].

Digital image correlation (DIC)—an optical method to measure changes in images—usually requires black spots on the specimen, for its analysis. This method may be able to detect the stress concentration on the SPB. However, it is not suitable to study the shape of SPBs, as ink spots on the thin film may affect its strength and weight properties.

To overcome this problem, we developed a Simplified DIC (SiDIC) method using an intersection detector, which allowed us to track the diamond-shaped weave of the net so that we could measure the deformation of the SPB during the pressurization process. In this study, we developed the SiDIC method and verified the measurement accuracy, using a rubber balloon and diamond-shaped polymer net.

2. Simplified Digital Image Correlation Method

SiDIC method is a simple deformation measuring method. Instead of reading the luminance values of the image, SiDIC method recognizes the movement of the intersections to measure the deformation. Fig.1 shows how SiDIC method measures the deformation. As shown in Fig.1, SiDIC method reads the intersections of the net covering the balloon. The SiDIC method calculates the amount of deformation by reading the coordinates of the intersections. First, we read the coordinates of the intersections before and after deformation. The polymer net used this time was not a point but a line where the intersection of the net intersects. Therefore, there is no clear intersection in the image captured. In this experiment, the center of the line was defined as the intersection of the net. After reading the coordinates of the intersections, Eq.1, 2 is used to calculate the amount of displacement. As a result, SiDIC method measures the displacement from the amount of movement in the x and y directions before and after deformation of each intersection.

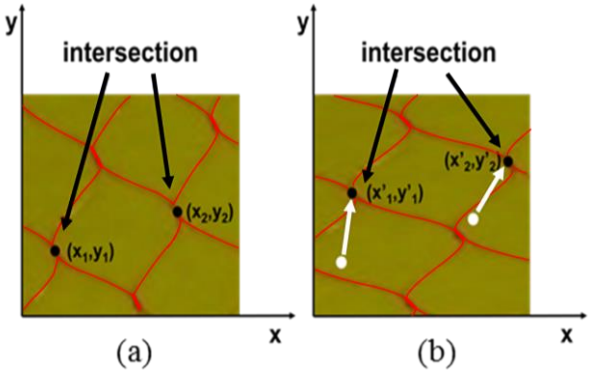

Figure 1. Coordinates of net intersections before and after deformation. (a) Reference image; (b) Deformed image.

$$\Delta x_1 = (x'_1 - x_1) \tag{1}$$

$$\Delta y_1 = (y'_1 - y_1) \tag{2}$$

3. Experiments using the DIC and SiDIC method applied to a rubber balloon

3.1. Experimental setups

To verify the measurement accuracy of the SiDIC method, a balloon which not only has random spray patterns but also covered by a net was used as shown in Fig.2 (a). This makes it possible to analyze even with the DIC method. To test whether the DIC and SiDIC method can be applied to the actual SPB, a rubber balloon that is covered just with a net as shown in Fig.2 (b) was used.

Generally, the measurement of three-dimensionally deformed object is measured using the three-dimensional image correlation method. Since the planar limitation comes from the two-dimensional nature of the images shot by the camera, the solution is to use more than one camera. From images taken from two different angles of the same object, it is possible to estimate its three-dimension shape [10]. In this method, it is assumed that two-dimensional deformation measurement using the DIC method of each image taken from different angles is performed correctly. Therefore, in this research, we confirm whether the 2-Dimensional deformation measurement of each image is done correctly. In this experiment, a digital camera is used to take an image of the balloon before and after deformation. Therefore, not the actual deformation of the surface of the balloon but the two-dimensional deformation amount on the image is measured. To measure the amount of deformation from the image, the unit of deformation amount is "pixel".

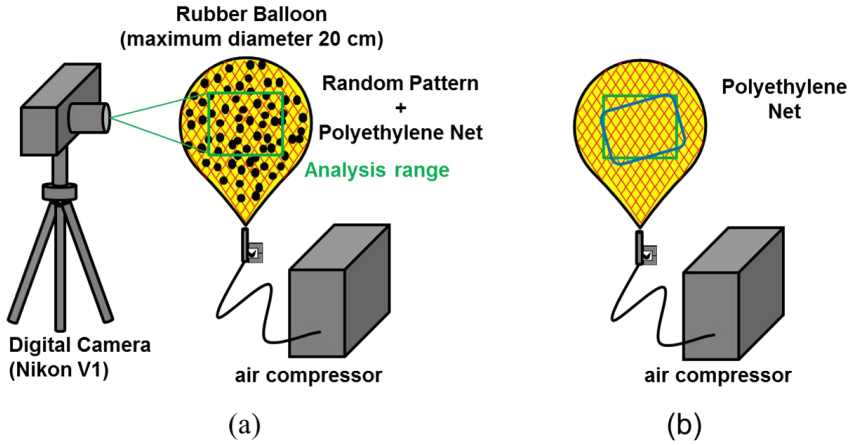

Figure 2. Experimental setups for the displacement measurement. (a) Net + spray pattern (b) Plastic net

3.2. Measurement accuracy of the SiDIC method compared by the result of DIC method

Next, measurement accuracy of SiDIC method was verified by using balloon (b) in Fig.2. Figure 3 shows the displacement distribution in the x-direction obtained from the DIC analysis. We analyzed the deformation at the dotted line using the SiDIC method and compared the results with the DIC method. Figure 4 shows the compared results. The line is the results of DIC method and the plots are the results by SiDIC method. The results by the SiDIC method almost agree with the result by the DIC method and found that the SiDIC method can also measure accurately.

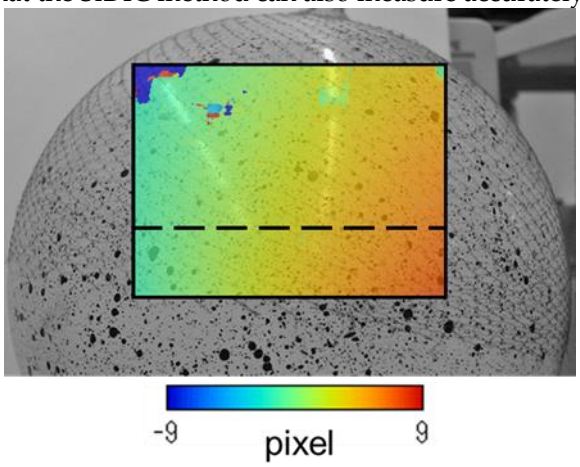

Figure 3. Horizontal displacement distribution by the DIC method on the photograph of random spray patterned and net covered balloon

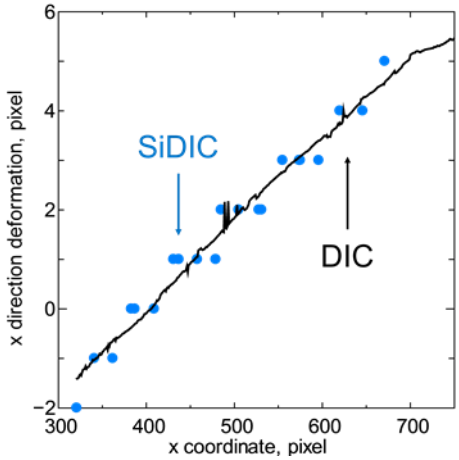

Figure 4. Displacement of horizontal direction on the dotted line in Fig.3 calculated by the DIC and SiDIC method

3.3. Measuring the displacement of the balloon covered with the net using the DIC method

Next, the DIC method was applied to a balloon covered just with the net shown in Fig.3(b). As a result, x-direction deformation distribution map shown in Fig.5 (a) was obtained. Also, the SiDIC method was applied and as a result, Fig.5 (b) shows the x-direction deformation distribution map. Fig.5 (a) shows that most parts of the net were read surely, though some were not measured properly such as the area inside the red circle in the figure. Since the DIC method reads the luminance value, it causes error, as it cannot be accurately measured depending on the image. We analyzed the deformation at the dotted line and compared the results of the DIC and SiDIC method. Fig.6 was obtained by the results. As you can see from Fig.6, the DIC method could not measure the displacement surely, though the SiDIC method measured the smooth deformation. The SiDIC method outputs fewer number of results because of less data, though since it does not cause errors as the DIC method, it is a method that enables stable analysis. The reason why the DIC method caused errors is that of the lighting and the DIC method misrecognized deformation of the net intersections. Fig.7 shows an example of the misrecognition algorithm. From Fig.7, the intersection moved to point (2) after deformation. The DIC method errors occur when it misrecognized the after deformation

point as (1) or (3). On the other hand, the SIDIC method read the coordinates of the intersections to prevent errors and to measure the deformation.

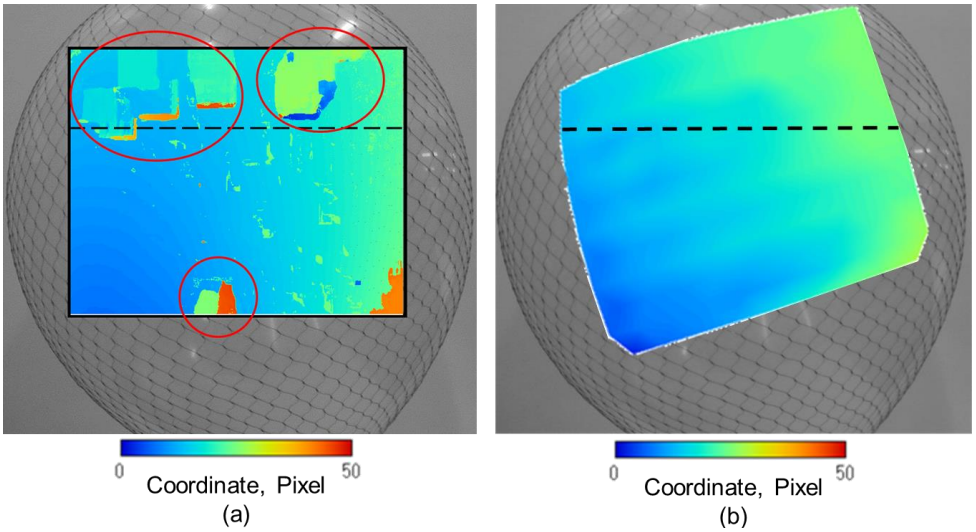

Figure 5. Horizontal displacement distribution by (a) DIC; (b) SiDIC, method on the photograph of net covered balloon

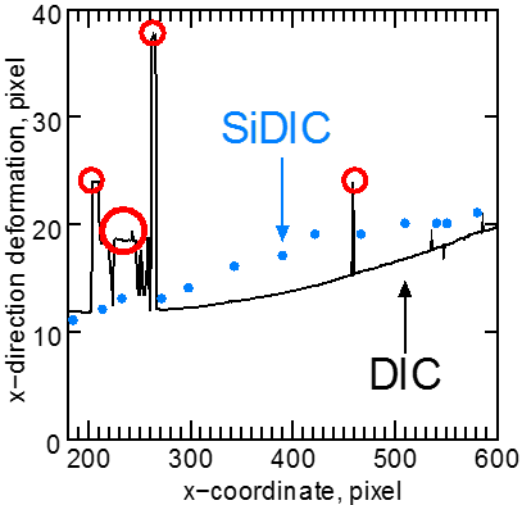

Figure 6. Displacement of horizontal direction on the dotted line in Fig.5 calculated by the DIC and SiDIC method

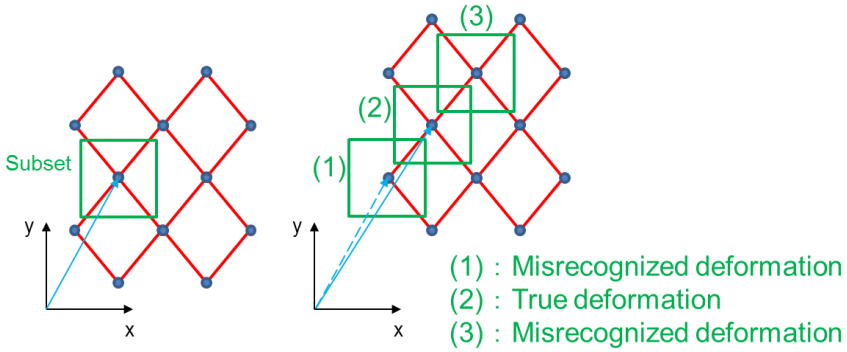

Figure 7. Misrecognition of the deformation of the net by DIC method

4. Conclusion

In this research, Simplified Digital Image Correlation (SiDIC) method for detecting non-uniform deformation of the Super pressure balloon was developed. In order to confirm the measurement accuracy of the developed SiDIC method, the analysis result of the DIC method and SiDIC method

were compared. As a result, the SiDIC method measured the deformation more accurately for the deformation of the balloon covering the net. Moreover, the result of the deformation restricted balloon measured by the SiDIC method, it showed that the SiDIC method can measure no deformation properly. Therefore, it can be used as a simple deformation measurement method of the balloon.

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