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Engineering Notes

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Evaluation of Characteristic and Degree of Wrinkles in Space Membrane Structures

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Nomenclature

d	=	interpixel distance
i, j	=	pixel level
L	=	gray level of image
P_θ	=	cooccurrence matrix in θ direction
$p(i, j)$	=	frequency

I. Introduction

MEMBRANE is one of the most important materials in space membrane structures [1]. Because of the small bending stiffness, the wrinkles will occur in the membrane when the membrane subjects to the action of the compressive stress. The wrinkles drastically alter the structural performance and decrease the effective structural size. A better understanding of the characteristic and degree of the wrinkles in the membrane is essential and desirable [2]. Figure 1 is the model of a space inflatable antenna reflector, which is developed in Harbin Institute of Technology in People's Republic of China. The material of the reflector is the membrane and the wrinkles occur at the outside circular edges. Research on the wrinkles in the membrane structure is mainly focus on the characteristic and degree of the wrinkles.

The wrinkles contain the physical texture features and the obvious wave crest and trough. Figure 2 shows the wrinkle texture image. The obvious variation of the gray degree can be obtained from the wrinkle texture image, thus, the gray-level cooccurrence matrices (GCM) method is presented to determine the distribution and direction of the wrinkles. For a very large-scale space membrane structures, the wrinkle experiment and numerical computation are both difficult and complex [3]. However, the GCM method can be performed by using several wrinkle images and the wrinkle images can be easily obtained by taking photos. Therefore, the GCM method is very suitable for the wrinkle characteristic analysis.

The GCM method is a newly emerging method in evaluating the wrinkling degree of the fabric. Some tentative discussions have been performed by several researchers. In 1995, Zhang and Bresee [4] presented that the degree of wrinkle in the fabric can be determined according to wrinkle intensity, configuration, power spectral density, degree of random, and fractal. Wang et al. [5] analyzed the grain characteristics of the image of fabric wrinkle based on the image analysis. However, they did not perform the analysis of the evaluation of the wrinkling degree of the fabric. Thus, it is very difficult to apply these methods and data to exactly evaluate the characteristic and degree of the wrinkles in space membrane structures. An effective method (GCM method) is necessary to be presented to accurately determine the degree and characteristic of the wrinkles in space membrane structures.

This paper describes the use of a method by which GCM are used to determine the direction and distribution of wrinkles in space membrane structures. Statistical measures, including angular second moment (ASM), contrast (CON), correlation (CORR), entropy (ENT), and inverse different moment (IDM) are calculated based on gray levels, and the results are used to characterize the average wrinkling characteristics in each sampled region. A wrinkling experiment is done to verify the predictions of the GCM method on the distribution and degree of wrinkles in the membrane.

II. Theory of GCM

A. GCM

The GCM is a second-order statistical tool, and it is very useful to characterize the texture features. It is a representation of the spatial relationship of gray levels in an image, and an important characteristic for the automated or semi-automated interpretation of the digital images. It can be specified in a matrix of relative frequencies $p(i, j)$, with which two neighboring pixels are separated by distance d and angle θ, one with pixel level i and the other with pixel level j. Such matrices of the spatial dependence frequencies are symmetric and calculated within a sliding window. For each matrix, various measures related to the spatial distribution of the gray levels can be derived [6,7].

The GCM are the conditional joint probabilities of all pair wise combinations of the gray levels (i, j) in the fixed-size spatial window given two parameters: interpixel distance d and orientation θ.

For the given distance d, we can get four different cooccurrence matrices $P_{0\ \mathrm{deg}}$, $P_{45\ \mathrm{deg}}$, $P_{90\ \mathrm{deg}}$, and $P_{135\ \mathrm{deg}}$ at four different orientations $\theta = 0$, 45, 90, and 135 deg. For different orientations, the distances are given by the following expression:

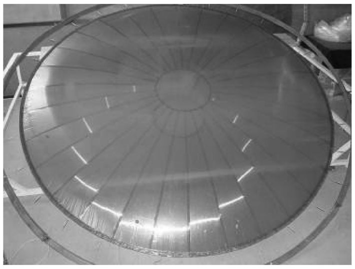

Fig. 1 Space inflatable antenna reflector model.

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$$\begin{cases} \theta = 0 \text{ deg}; & |x_1 - x_2| = d, \quad |y_1 - y_2| = 0 \\ \theta = 45 \text{ deg}; & x_1 - x_2 = d, \quad y_1 - y_2 = d; \quad \text{or} \quad x_1 - x_2 = -d, \quad y_1 - y_2 = -d \\ \theta = 90 \text{ deg}; & |x_1 - x_2| = 0, \quad |y_1 - y_2| = d \\ \theta = 135 \text{ deg}; & x_1 - x_2 = d, \quad y_1 - y_2 = -d; \quad \text{or} \quad x_1 - x_2 = -d, \quad y_1 - y_2 = d \end{cases} \tag{1}$$

where $f(x_1, y_1) = i, f(x_2, y_2) = j, i = 0, 1, \cdots, L-1; j = 0, 1, \cdots, L-1$. L is the gray level of the image.

In the image processing, the direction pattern of the wrinkle image can be determined according to $P_{0\ \text{deg}}$, $P_{45\ \text{deg}}$, $P_{90\ \text{deg}}$, and $P_{135\ \text{deg}}$. The GCM lies on the parameter d and θ. The distribution of the wrinkle is relevant to the distance d and the direction of the wrinkle is related to the angle θ.

B. Extracting the Wrinkle Texture Features

The texture feature of the wrinkle image, including direction and pattern, can be derived by using the GCM method. Because there are a lot of dates in the GCM, it is very difficult to apply it to interpret the images straightly.

To generate the texture features based on the cooccurrence probabilities, the statistics are applied to the probabilities. Generally, these statistics identify some structural aspects of the arrangement of probabilities stored within a matrix, which in turn reflects some qualitative characteristics of the local image texture.

Some statistical measures can be derived from the cooccurrence matrix [8]. Five measures we used here, named ASM, CON, CORR, ENT, and IDM, have definitions given by the following expressions.

The central difference method is stable for a time step increment satisfying the following relationship:

1) ASM is the measure of the uniform of the wrinkle.

$$\text{ASM} = \sum_i \sum_j \{p(i,j)\}^2 \tag{2}$$

2) CON is the measure of the variation of the local gray of the wrinkle.

$$\text{CON} = \sum_i \sum_j (i-j)^2 p(i,j) \tag{3}$$

3) CORR is the measure of the correlation of the local gray of the wrinkle.

$$\text{CORR} = \frac{\sum_i \sum_j (ij) p(i,j) - \mu_x \mu_y}{\sigma_x \sigma_y} \tag{4}$$

where $\mu_x = \sum_i i \sum_j p(i,j)$, $\mu_y = \sum_j j \sum_i p(i,j)$, $\sigma_x = \sum_i (i - \mu_x)^2 \sum_j p(i,j)$, and $\sigma_y = \sum_j (j - \mu_y)^2 \sum_i p(i,j)$

4) ENT is the measure of the complications and heterogeneity of the texture of the wrinkle.

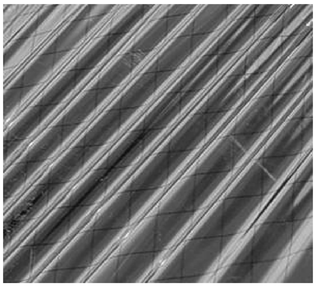

Fig. 2 Wrinkle texture image.

$$\text{ENT} = -\sum_i \sum_j p(i,j) \log[p(i,j)] \tag{5}$$

5) IDM is the measure of the local uniform of the wrinkle.

$$\text{IDM} = \sum_i \sum_j \frac{1}{1 + (i-j)^2} p(i,j) \tag{6}$$

III. Wrinkling Experiment

The thickness of the Kapton membrane material is 0.025 mm, and the membrane is fixed on the metal frame along two parallel edges. The other two sides are free. The length and width of membrane structure are 380 and 128 mm, respectively. The material density is 1420 kg/m^3, Young's modulus is 3.53 GPa, and the Poisson ratio is 0.3. The wrinkles will occur when one moves the fixed ends in the longitudinal diagonal direction. The wrinkle gray image is shown in Fig. 3.

The local regular wrinkle areas are extracted from the experimental wrinkling images and shown in Fig. 4. They are named the computation samples.

IV. Results and Analysis

In their most general form, the cooccurrence matrices are time-consuming to compute and are memory intensive as well. A prior quantization on the pixel values is usually performed, for instance, 256 gray levels quantized to 16 gray levels reduces the dimensionality of the cooccurrence matrix from 256×256 to 16×16. The GCM $P_{0\ \text{deg}}$, $P_{45\ \text{deg}}$, $P_{90\ \text{deg}}$, and $P_{135\ \text{deg}}$ of every sample at four different orientations $\theta = 0$, 45, 90, and 135 deg are determined. Then, the texture features of the wrinkle image can be obtained according to the value of the GCM. The comparison of the value of the texture features is listed in Table 1.

It can be observed from the comparison of the sample a and the sample b that the wrinkle texture in the sample b is denser than the texture in the sample a. This result is obtained according to the following explanation. The value of ASM of the sample a is less than that in the sample b. The value of CON of the sample a is less than that in the sample b. The absolute value of CORR of the sample b is less than that in the sample a. The value of ENT of the sample a is less than that in the sample b. The value of IDM of the sample a is less than that in the sample b. The prediction shows good agreement with the results of wrinkle experiments.

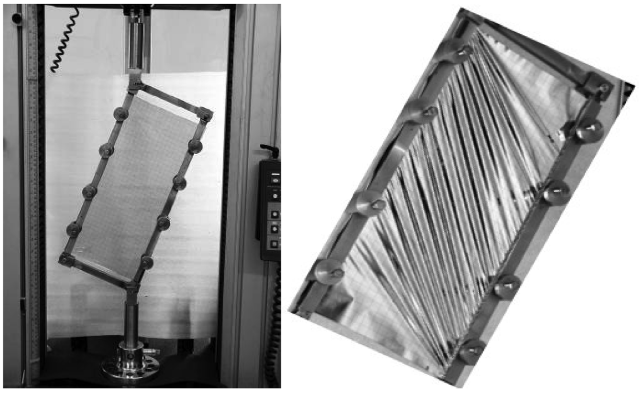

Fig. 3 Wrinkle texture experimental instrument and image.

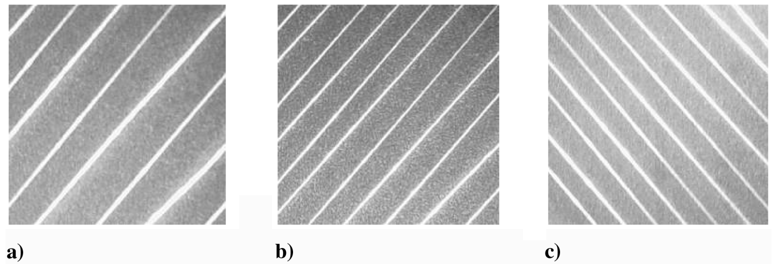

Fig. 4 Computation samples.

Table 1 Texture feature of the wrinkle image

Sample	Angle, deg	ASM	CON	CORR	ENT	IDM
a	0	2.6832	6.2779	−2.4416e-005	6.4820	3.9216
	45	2.8927	11.5530	−1.4782e-005	7.5235	4.1060
	90	2.5171	2.3140	−4.4999e-005	5.2032	3.7913
	135	2.5692	2.6919	−3.7101e-005	5.4651	3.8589
b	0	6.7744	43.592	−3.1048e-007	20.990	8.9770
	45	7.9507	102.09	−1.4976e-007	25.902	9.3653
	90	6.1307	26.537	−4.8061e-007	18.455	8.6658
	135	8.1522	33.386	−2.0101e-007	19.826	9.2190
c	0	4.3868	22.000	−1.5990e-006	16.010	6.6693
	45	5.1535	15.244	−1.1320e-006	14.862	7.6612
	90	3.5321	11.987	−4.1081e-006	13.045	5.9787
	135	5.6903	49.857	−1.0625e-006	18.833	7.7017

The texture features in four different directions of the sample a and the sample c are compared. The results show that the wrinkle texture direction can be judged by comparing the texture features in four directions. It can be observed from the sample a that the value of ASM, CON, CORR, ENT, and IDM in the direction of 45 deg is greatly different from other directions. The same characteristic can also be seen from the sample c. The specific direction in the sample c is 135 deg. We can conclude that the wrinkle texture direction of the sample a and the sample c is perpendicular with each other, which is well agreed with the experiment.

The conclusions can be obtained from the results in Table 1 that the degree of closeness of wrinkle texture in wrinkle images can be determined by using the GCM method. The wrinkle direction can be obtained by comparing the eigenvalue in different direction.

V. Conclusions

The GCM method is used to determine the characteristic and degree of the wrinkles in space membrane structures. Several statistical measures are calculated based on the gray levels, and the results are used to characterize the average wrinkling characteristics in each sampled region. The predictions are compared with a wrinkling experiment, and the results reveal that the distribution and degree of the wrinkles in the membrane can be exactly determined by using the GCM method.

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