Evaluating and Improving the Orange Peel Texture of Foldable Screens

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Abstract

We introduced a novel support film, to improve the reflection image distortion (RID) induced by orange peel textures on the off-state foldable screens. We evaluated the improvement using an Orange Peel Index (OPI) that closely aligns with human visual perception. The evaluation results demonstrated that this new support film significantly improved the screen flatness.

Author Keywords

Foldable Screen; Foldable Display; Reflection Image Distortion; Orange Peel; Support Film; Cuvature Distribution; Human Visual; UTG.

1. Introduction

In the evaluation of surface quality for foldable screens, orange peel-like texture is a common surface defect that significantly impacts visual performance. This effect arises from microscopic geometric irregularities introduced during screen processing, typically manifesting as undulating patterns reminiscent of an orange peel. These undulations, usually at the micron scale, are not readily visible to the human eye. However, when ambient light illuminates the screen, the irregular surface scatters light, leading to a cumulative effect that distorts the reflected image, known as Reflection Image Distortion (RID). This phenomenon adversely affects the user's visual experience, particularly when the foldable screen is in a dark state. Figure 1 shows the reflection image distortion observed under dark-state conditions, where the reflected image of a light tube appears severely distorted on the screen. The circled area highlights a typical instance of RID caused by orange peel texturing.

Due to the characteristics of its materials and manufacturing processes, foldable screens are prone to RID. This arises because the materials tend to develop microscopic irregularities during bending and stretching, which reduce surface flatness and increase the occurrence of RID. Currently, RID has become a significant issue in evaluating the surface quality of foldable screens.

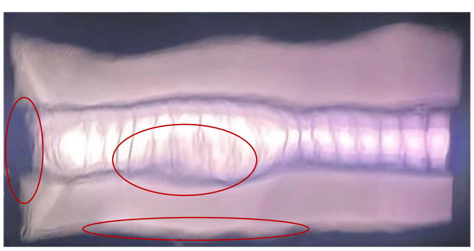

Figure 1. Reflection Image Distortion Caused by Orange Peel Texture

2. Optical Principles of RID

To explain this phenomenon from an optical perspective, we constructed a model that links surface topography, reflected light, and human visual perception. First, we assume that the screen surface morphology can be described by a function, representing the height deviation from an ideal flat plane. To study the reflection of light on this surface, it is necessary to determine the normal vector at each point on the surface. Given that the microscopic undulations of the surface are typically very small, the unit normal vector can be approximated as:

$$\hat{\mathbf{n}} = \left(-\frac{\partial f}{\partial x}, -\frac{\partial f}{\partial y}, 1 \right) \tag{1}$$

According to the law of reflection, the direction of the reflected light can be determined by the direction of the incident light and the surface normal vector. Assuming that the incident light is perpendicular to the average plane of the screen, the direction of the reflected light is given by:

$$\hat{\mathbf{s}}_r = \left(-2\frac{\partial f}{\partial x}, -2\frac{\partial f}{\partial y}, 1 \right) \tag{2}$$

Equation (2) indicates that the reflected light deviates from the ideal reflection direction. For a small-angle approximation, the angular deviation of the reflected light is given by:

$$\theta_x \approx \delta_x = -2\frac{\partial f}{\partial x}, \quad \theta_y \approx \delta_y = -2\frac{\partial f}{\partial y} \tag{3}$$

The angular deviation of the reflected light leads to a displacement of the perceived reflected image on the screen plane. Since curvature reflects the rate of change in the gradient, the spatial rate of change in the angular deviation of the reflected light can be described by Equation (4). Consequently, the spatial rate of change in the reflected image distortion displacement is directly correlated with the surface curvature. Given that the distance between the human eye and the screen is D, the RID caused by the cumulative effect of displacement deviation can be expressed by Equation (5).

$$\frac{\partial \theta_x}{\partial x} = -2\kappa_x, \quad \frac{\partial \theta_y}{\partial y} = -2\kappa_y \tag{4}$$

$$\Delta x(x,y) = -2D\int_{x_0}^{x}\left(\int_{x_0}^{x'} \kappa_x\left(x''\right)dx''\right)dx'$$
$$\Delta y(x,y) = -2D\int_{y_0}^{y}\left(\int_{y_0}^{y'} \kappa_y\left(y''\right)dy''\right)dy' \tag{5}$$

The quantitative relationship between surface height deviation and RID perceived by the human eye demonstrates that reducing fluctuations in surface curvature can effectively mitigate RID. To validate the above theory, we simulate the reflection process of light on screen surfaces with varying curvature to quantitatively analyze the impact of surface curvature on the displacement of the reflected image. In the experiment, we use actual measured curvature data to calculate the displacement of the reflected image on the observation plane, recording the average and maximum displacement values for each curvature level.

Table 1. Calculation Results of Reflection Displacement under Different Curvatures

Curvature	AverageDisplacement/(mm)	MaxDisplacement/(mm)
-1.1e-04	4.25e-05	7.78e-05
-0.10	3.75e-04	6.86 e-04
-0.17	6.57 e-04	1.20 e-03
-0.27	1.03 e-03	1.89 e-03
-0.60	2.31 e-03	4.23 e-03
-1.16	4.49 e-03	8.21 e-03
-1.87	7.24 e-03	1.32 e-02

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The results in Table 1 show a clear positive correlation between the average and maximum displacement of the reflected image and the increase in curvature. The calculated average displacement ranges from 4.25e-05 mm to 7.24 e-03 mm, which is sufficient to elicit human perception of RID. This experiment validates the theoretical derivation, highlighting the physical mechanism of RID: microscopic surface irregularities induce changes in the normal vector, causing deflection in the direction of reflected light, which subsequently results in RID. This study provides theoretical and empirical support for understanding and controlling RID in foldable screens under dark-state conditions, offering valuable insights for improving screen manufacturing processes and enhancing product quality.

3. Orange Peel Index

In this study, we propose a quantitative evaluation method for RID in foldable screens under dark-state conditions, based on curvature data. This method combines local curvature variation with human visual weighting to derive an index that reflects the severity of reflection distortion on the screen surface, referred to as the Orange Peel Index (OPI). Specifically, we use Phase Modulation Deflection (PMD) technology to obtain true minimum curvature data from the screen surface, where minimum curvature represents the lowest bending degree of the surface at a given point in a specific direction. This corresponds to the direction in which the surface is most concave locally at that point. Human perception of surface smoothness or glossiness is closely related to local curvature variations, as the visual system is particularly sensitive to slight protrusions and depressions. Minimum curvature highlights the most “flat” or “concave” regions of the surface locally, which are often the main sources of RID. Therefore, minimum curvature can directly assess the severity of the orange peel effect, with smoother surfaces having minimum curvature values closer to zero. Subsequently, by calculating a weighted function related to visual perception based on local curvature variation, we quantify the overall orange peel effect index. This method provides a more precise assessment of screen surface flatness and its impact on user experience by integrating physical geometric characteristics with visual perception factors.

The OPI is calculated as a weighted average of local curvature variations across different regions in the curvature matrix, with weights based on human visual sensitivity. This method consists of three main steps.

Calculation of Local Curvature Variation: To assess surface flatness at each location, we first calculate the local curvature variation by defining a movable window. Local curvature variation is represented by the root mean square (RMS) error, which serves as a measure of dispersion and can accurately capture changes in local undulations at each point on the surface. Regions with larger RMS values indicate more pronounced local undulations, which may lead to stronger RID. The formula for calculating the local RMS error is given by Equation (6), where A is the total number of pixels within the window, and B represents the window centered on. This formula is based on a benchmark of zero, representing the curvature of the ideal flat state. This method directly reflects absolute deviation at each point, making it more sensitive to abrupt changes in the assessment of RID.

$$RMS_{i,j} = \sqrt{\frac{1}{|W|}\left(\sum_{(m,n)\in W_{i,j}} K(m,n)^2\right)} \quad (6)$$

Calculation of Visual Weighting: The calculation of visual weighting is achieved by convolving the curvature matrix with a Laplacian of Gaussian (LoG) filter. The LoG filter we use is defined by Equation (7). When quantifying the geometric characteristics of a foldable screen surface, directly processing the curvature map may obscure critical local features. The irregularities typical of orange peel texture often exhibit mid- to high-frequency characteristics, and the LoG filter effectively emphasizes local spatial frequency variations. Based on Fourier analysis, local undulations of the surface can be decomposed into a series of frequency components, with areas of intense curvature change containing more mid- to high-frequency elements. Applying visual weighting to these areas better simulates the human eye’s sensitivity to mid-frequency curvature changes, thus highlighting regions of the orange peel effect that are most perceptible, avoiding their dilution by smoother areas.

$$\mathrm{LoG}(x,y) = \frac{1}{\pi\sigma^4}\left(1-\frac{x^2+y^2}{2\sigma^2}\right)\exp\left(-\frac{x^2+y^2}{2\sigma^2}\right) \quad (7)$$

Summary of Weighted Local Curvature Variation: As shown in Equation (8), by combining local curvature variation with global visual weighting, this method enables a comprehensive assessment of RID in foldable screens. Regions with significant curvature discontinuities (i.e., areas with large RMS errors) contribute more heavily to the overall Orange Peel Index (OPI), meaning that a higher OPI value indicates more pronounced RID on the screen surface.

4. Experiment & Discussion

First, we conducted an experimental analysis of the window size required for evaluating the OPI. As shown in Figure 1, the the window size determines the neighborhood range involved in the local RMS error calculation, thereby directly affecting the sensitivity to surface features of different spatial scales. According to Figure 2, when analyzing the OPI of measured data, the index exhibits a non-monotonic trend as the window size increases: initially decreasing, then rising, and finally decreasing again. This trend can be described by Equation (8), where S(f) represents the power spectral density of the surface texture, and the sinc term in the integral expression captures the window's weighting effect on different frequency components.

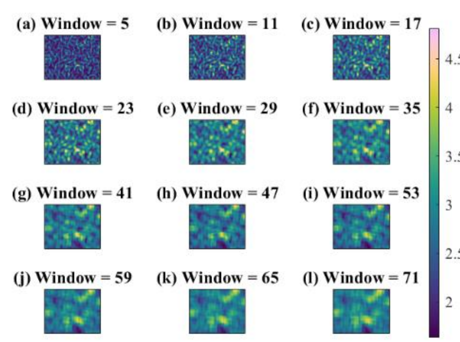

Figure 2. Influence of Window Size on Local RMS Error Calculation

When the window size is small, the local RMS error calculation is primarily influenced by high-frequency noise and fine textures, resulting in a higher OPI. As the window size increases, these high-frequency components are averaged over a larger neighborhood, reducing the noise effect, and thus the index decreases. However, as the window size continues to grow, it begins to encompass mid-scale surface undulations, with an increased influence from mid-frequency components, such as ripples and surface irregularities. These features intensify local variations, causing the OPI to rise. Finally, when the window size becomes too large, local differences are further averaged out, and the overall surface is perceived as flat, leading the index to decrease once.

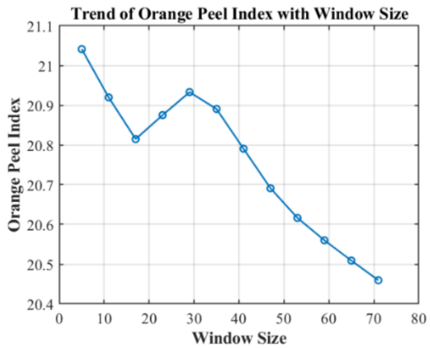

Figure 3. Non-Monotonic Trend of Orange Peel Index with Increasing Window Size

$$RMS_{i,j}^{\ 2}=\int_{f_{\min}}^{f_{\max}} S(f)\left[\frac{\sin(\pi f w)}{\pi f w}\right]^2 df \qquad (8)$$

The window size should correspond closely to the actual scale of the orange peel texture features. To accurately determine the typical scale of these features, as shown in Figure 5, we performed a radial average of the Power Spectral Density (PSD) to obtain the frequency energy distribution curve and identified the characteristic frequency corresponding to the energy peak. By taking the inverse of this characteristic frequency, we calculated the typical scale of the orange peel texture. This characteristic scale provides a basis for selecting an appropriate window size, ensuring that the window effectively suppresses high-frequency noise while accurately capturing the critical features of the orange peel texture in the OPI calculation.

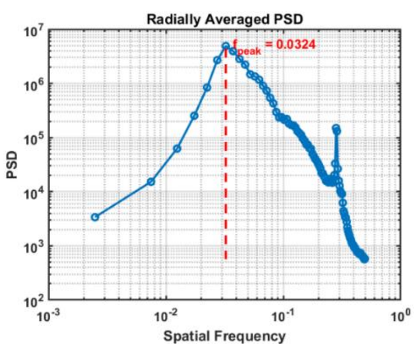

Figure 4. Frequency Energy Distribution Curve form Radial Averaged PSD

Another parameter σ, determines the scale of the filter and its sensitivity to features of different spatial frequencies. As shown in Figures 6 and 7, experimental analysis with σ values ranging from 1 to 6 reveals a decreasing trend in the OPI as σ increases. This occurs because larger σ values reduce sensitivity to small-scale textures, weakening the response of the visual weighting matrix to subtle surface undulations, thus resulting in a smoother weighted local variation matrix and reduced local differences. Based on this observation and validation through visual experiments, a setting of σ=3 is considered reasonable.

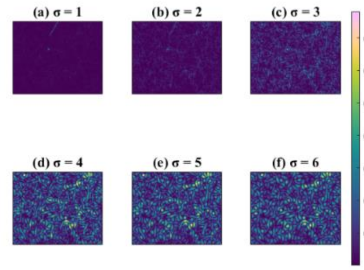

Figure 5. Effect of Parameter σ on Sensitivity in OPI Calculation

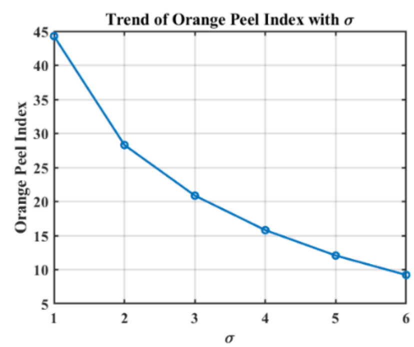

Figure 6. Decreasing Trend of OPI with Increasing σ Value

We further applied OPI to evaluate samples of the new support film and found a significant improvement in flatness compared to the mass-produced foldable displays. The evaluation results are shown in Figure 7. Among the three samples analyzed, Sample 1 and Sample 2 represent two distinct mass-produced foldable screens currently on the market, while Sample 3 incorporates a new supporting film. The OPI for the currently mass-produced foldable screens ranges from 0.85 to 0.95, while the OPI for Sample 3 is considerably lower at 0.36, indicating a decline of 50% to 62%.

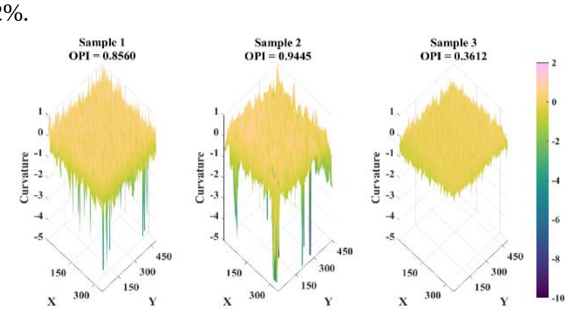

Figure 7. Comparison of OPI Results and Visual Ranking of RID Severity for Different Samples

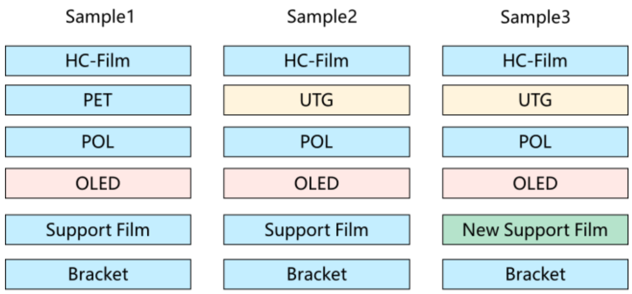

Figure 8. Schematic Diagram of the Structures of the Three Experimental Samples

Figure 8 presents the structural schematics of the three foldable modules. We believe that this notable reduction in OPI is correlated with the increased rigidity of the module structure. Comparison of the structural rigidity of the core layer within the module revealed that Sample 2 exhibited a 137% improvement over Sample 1, while Sample 3 demonstrated a 221% improvement. Moreover, we posit that the enhanced rigidity of the under-screen structure significantly impacts flatness improvement, as demonstrated by the absence of substantial enhancement in Sample 2 compared to Sample 1.

5. Conclusion

In this study, we improved the issue of Reflection Image Distortion (RID), especially the orange peel texture on the off-state foldable displays by introducing a novel support film. To quantitatively evaluate the improvement, we proposed the Orange Peel Index (OPI). This index combines local curvature variation with human visual weighting factors, enabling it to capture both the physical surface characteristics and their perceptual impacts, thereby providing an effective metric for RID assessment. We made a novel sample based on the UTG and the new support film, and achieved a 62% reduction on the OPI. We believe that enhancing the structural rigidity of foldable screens can substantially improve their flatness, particularly through the reinforcement of materials beneath the screen. We will further investigate the improvement of flatness in foldable displays by evaluating various types of the RID and assessing the impact of production processes.

6. References

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