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Paper Session II-B - 3-Dimensional Feature Mapping Using Spatial Spectral Analysis

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3-DIMENSIONAL FEATURE MAPPING USING SPATIAL SPECTRAL ANALYSIS

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ABSTRACT

Orbiter vehicles are routinely exposed to a variety of small scale debris while operating in low earth orbit. Impacts with such debris often result in surface and/or subsurface damage to orbiter windows. Current procedures require windows to be manually inspected for impact damage after each shuttle mission.

Once identified, surface damage feature depths are determined by analyzing mold impressions of the damaged areas. Subsurface damage always results in window rejection since the depths of subsurface features are deemed "unmeasurable" using standard mold impression measurement techniques.

This paper presents an automated optical technique for measuring the depth of small scale surface and subsurface damage features in orbiter windows. Test results based on actual orbiter window damage features are also presented.

INTRODUCTION

The I-NET Special Instrumentation Laboratory (SPIL) has recently been tasked with developing a system to inspect orbiter windows during orbiter processing operations at the OPF. The system will be required to scan the entire window surface to detect both surface and subsurface impact damage. Once identified, each damage feature will require detailed analysis to determine the depth extent of the damage.

Current plans call for the inspection process to be divided into two phases. The first phase will involve scanning the entire window surface to locate all surface and subsurface impact damage features. Tests using a commercially available optical scanner have demonstrated that a CCD line array scanner is capable of detecting both surface and subsurface damage features. A damage feature database will be maintained for each window to ensure that only new damage features are singled out for detailed analysis.

The second phase of the inspection process will employ a high resolution CCD camera system to perform detailed analysis of the damage features detected during the initial window scan. The principle objective during this phase of the inspection process is to determine the maximum depth extent of the damage features. This paper describes one possible method of making such depth determinations.

TECHNICAL APPROACH

The spatial spectral analysis technique described here is closely related to the operation of the optical micrometer or refocus microscope. A refocus microscope uses a simple change in object distance to measure the depth of surface features. The micrometer is placed on the measurement surface and adjusted until the surface area surrounding the feature to be measured is in clear focus. After noting the micrometer setting the instrument is refocused on the deepest portion of the surface feature. The measured depth is then taken as the change in micrometer setting (object distance). Refocus microscopes have traditionally been used to measure surface features on opaque materials. The instrument can, however, often be used to measure depths of surface and subsurface features in translucent materials.

The refocus approach to depth measurement can be largely automated by employing digital imagery and spectral analysis. In essence, a computer can determine when an image (or portion thereof) is in focus by examining the spatial frequency components of a series of object plane images. Well focused images are characterized by increased energy in the high frequency components. The points at which an image comes into focus can therefore be determined by examining the relative changes in the spatial spectral characteristics of the object plane image sequence.

The basic procedure for determining the topography of surface or subsurface features using spatial spectral analysis is the same. The first step is to digitize a series of images containing the feature to be analyzed. For each image the object plane of the camera system is advanced a small distance into the window material. This is accomplished by advancing the position of the camera while maintaining a constant focal length.

After the overall image sequence has been digitized, a reference grid, which covers the areas

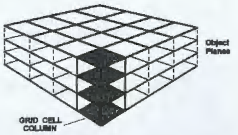

Figure 1. ***Object Plane Grid Geometry***

of interest, must be established. It is critical to ensure that the reference grid position and orientation are held constant for all images in the sequence. The grid cell size is somewhat arbitrary but it should be selected with lateral spatial resolution requirements in mind. If the collection of reference grids for a complete sequence of object plane images is thought of as a 3-dimensional structure, then the individual unit of analysis becomes a single grid cell column. The basic object plane grid geometry is shown in Fig. 1. Note that one of the grid planes must be selected to represent the surface of the window. Spectral analysis may be performed on as many grid cell columns as deemed necessary to fully evaluate surface or subsurface feature in question.

In order to analyze a grid cell column, a two dimensional Fast Fourier Transform (FFT) must be performed on each cell of the grid square column. Each complex FFT result must be further processed to produce a single statistic or discriminant which accurately describes the "high frequency energy" content of the object plane cell in question. The power spectral density function of each FFT is computed and scaled relative to the grid column maximum. A single "focal energy" statistic is then computed by integrating the two dimensional power spectral density function over the frequency range of interest.

Once the focal energy statistic has been determined for each object plane cell in the grid cell column, a profile of focal energy versus grid cell depth is constructed. Points at which the image cell is in focus are determined by searching for maximum values (i.e. peaks) in the focal energy profile.

If the feature being analyzed is an open pit (e.g. micometeoroid crater), the focal energy profile will have one peak representing the pit surface elevation. If, however, a subsurface fracture plane is being analyzed, the focal energy profile may exhibit peaks at both the window surface and the subsurface fracture plane depth.

Two important factors must be considered when analyzing focal energy profiles generated from FFTs. First, the algorithm requires identifiable, light scattering features to focus on. If any portion of the pit topography is relatively smooth and clean, the algorithm will find nothing to focus on. Second, the FFT measures spatial energy over the entire area of the grid cell. This being the case, grid positions at which the local surface topography is flat (relative to the object plane) will exhibit sharp, well defined peaks in the focal energy profile. Grid positions at which the local surface topography is relatively steep, on the other hand, will produce wider, flatter peaks, since different parts of the grid cell are in focus at different depths.

Finally, an important distinction must be made between surface and subsurface depth observations. Depths of subsurface features must be corrected for refraction. Orbiter windows are composed of fused silica which has a refractive index of about 1.46.

INITIAL TEST RESULTS

The first data set presented here was obtained from the LSOC training window supplied to the SPIL for test and evaluation purposes. The actual damage feature analyzed was a small open surface pit. The pit, which is shown in Fig. 2, is approximately 0.020" long and 0.008" wide. Fig. 2 also reveals evidence of a subsurface fracture in the form of surface cracks extending out from the ends of the open pit.

A series of 26 images, digitized with successively deeper object plane depths, were used to analyze the open surface pit and the adjacent subsurface fracture plane. The complete set of images is provided in Appendix A. The reference grid used to partition the object images is shown in Fig. 3. A grid cell size of 32 by 32 pixels (approximately 0.002" square) was selected. Individual image cells are identified by a pair of indices which apecify the row and column.

Cell (8,5), for example, refers to the 8th row and the 5th column. The object plane depth

Figure 2. ***Window Surface Pit***

ranged from 0.001" above the surface to 0.004" below the surface in 0.0002" increments. It should be noted that the actual location of the surface can be difficult to define. Not readily apparent from Fig. 2 is the fact that a portion of the window material in the impact zone is raised above the actual window surface. For the purposes of this analysis, a local surface reference for use in depth calculations was determined from the image data itself.

In order to compute the surface correction factor, a number of undisturbed areas near the open pit were selected for use as surface reference points. By performing spatial spectral analysis on these areas, the actual elevation of the window surface relative to the grid cell coordinate system was computed. The results of surface reference analysis, which are provided in Appendix B, revealed that the actual window surface is 0.0004" above the grid coordinate reference plane.

The first area analyzed was the open surface pit. Twenty grid cells, representing an area completely enclosed by the pit perimeter, were analyzed. The 20 focal energy profiles are provide in Appendix C. The maximum observed depth of 0.0016" occurred at grid cell (9,4). The actual maximum depth of 0.002" is found by subtracting the 0.0004" surface correction from the observed depth. The focal energy profile for grid cell column (9,4) is shown in Fig. 4.

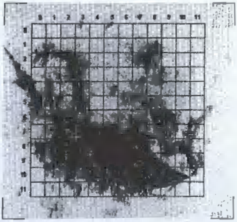

Figure 3. ***Analysis Grid Geometry***

The second area of interest was the subsurface fracture plane which appears to extend outward and downward from the open pit. Grid cell positions at which the fracture plane was clearly visible were somewhat limited due to the surface lighting geometry. In all a total of 12 grid cell columns were analyzed. The complete set of focal energy profiles is provided in Appendix D.

The maximum observed depth of 0.0028" occurred at grid cell positions (3,5) and (4,5). The actual maximum depth of 0.0047" is found by subtracting the 0.0004" surface correction and multiplying by the 1.46 refractive index. The focal energy profile for grid cell position (3,5) is shown in Fig. 5.

Note that the maximum subsurface fracture plane depth found here is not necessarily the deepest part of the fracture plane. It simply represents the deepest part of the plane which was visible at the time image sequence was captured. The lighting geometry used for this test was designed primarily to illuminate the open surface pit. A more detailed analysis with improved surface lighting would be required to fully characterize the subsurface fracture plane.

FOLLOW-ON TEST RESULTS

The second set of data presented here was obtained from a window which was removed from OV-103 just prior to STS-60. The damage feature, which is shown in Fig. 6 through 8, is a nearly circular pit approximately 0.030" in diameter. As with the previously discussed damage feature, sub-surface fracture planes were evident in the glass surrounding the pit.

The spatial spectral analysis performed on this damage feature was identical to the procedure described earlier. The depth of the pit, as determined from spatial spectral analysis was 0.0038". This result agrees closely with the depth derived from earlier mold impression measurments. The sub-surface fracture planes surrounding the pit were not analyzed.

The depth data derived from this data set was also used to generate a three dimensional representation of the pit topography which is shown in Fig 9.

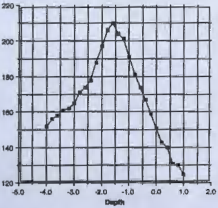

Figure 4. ***Energy Profile at Grid Cell (9,4)***

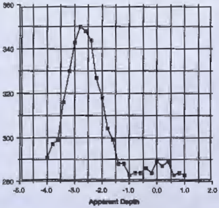

Figure 5. ***Energy Profile at Grid Cell (3,5)***

CONCLUSIONS

Determining damage feature depths using spatial spectral analysis appears promising. Unlike the current mold impression technique, spatial spectral analysis can be used to analyze subsurface as well as surface features.

This analysis used adjacent 32 x 32 pixel (approximately 0.002" square) grid cells and 0.0002" object plane spacing. Smaller grid cell size or overlapping grid cells could, however, be used to improve lateral resolution. In addition, an optical system with a shorter depth of field could be used in conjunction with closer object plane spacing to improve depth resolution.

It is important to remember that this process is inherently limited to identifying and measuring only those features which can be illuminated from the surface of the window. If this technique is utilized in a working instrument, camera lighting geometry will become a major area of interest.

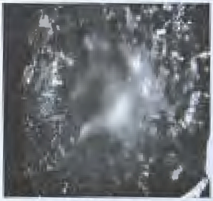

Figure 6. *Impact Pit (Surface)*

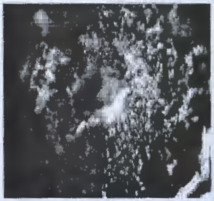

Figure 7. *Impact Pit (Mid Depth)*

Figure 8. *Impact Pit (Bottom)*

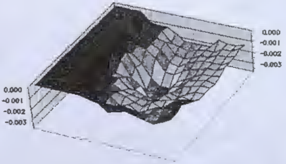

Figure 9. *3D Map of Window Pit*