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***SPECKLE PHOTOGRAPHY AND
DISPLACEMENT ANALYSIS OF
LARGE STRUCTURES***

A thesis presented in partial fulfilment of the
requirements for the degree of Doctor of Philosophy
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To the Glory of God

ABSTRACT

This research demonstrates the feasibility of a full-field photographic method for remotely measuring the movement of large deforming objects. 'Large objects' could include civil engineering structures such as dam walls, buildings and bridges, and geological phenomena such as glaciers. Such structures must be examined *in situ* and preferably by a non contacting method. The objective is to measure motion from time lapsed photographs of the moving object.

The method is based on speckle photography which is a well developed optical metrology technique for deformation measurement of engineering structures in laboratory conditions. Its application to large scale structures illuminated in sunlight at high imaging demagnifications has demanded some significant extensions and modifications to the technique.

Imaging these large objects offers a unique set of challenges which include the establishment of rigid tripods from which to take the time lapsed photographs in rugged glacial terrain, the variation of illumination in terms of both quality and angle of incidence, imaging through several kilometres of turbulent atmosphere and recording the signature texture of the object surface onto film at high imaging demagnifications. The effects of these factors are considered both conceptually and experimentally, providing fundamental understanding of the problem.

Displacement analysis is performed primarily by interrogation of time lapsed negative pairs using an unexpanded laser beam, as is generally the case in speckle photography. An automated system is developed to make practical the analysis of multiple points in the field of view. In parallel, a new digital technique is introduced where displacement results are obtained by pattern matching in digital versions of the speckle images. This analysis method is shown to be highly suitable for the application to glacier flow. Registration of the pair of time lapsed images is performed by calculating the affine transform describing the image misalignment (introduced at either the recording or analysis stage) within the non-deforming areas of the field of view. Use of this novel technique allows pairs of single exposures, rather than double exposures, to be examined, and it also increases the sensitivity of measurement.

Two dimensional motion fields representing glacier flow are presented, leading to the conclusion that the technique is feasible in sunlight illumination, for a variety of glacial surface types and at high imaging demagnifications.

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TABLE OF NOTATION

With reference to section number in thesis where symbol is first mentioned.

| | |
|--------------------------------|--|
| B | Stereoscopic baseline, 4.3.4. |
| $C_n^2(z)$ | A function describing the strength of turbulence along the optical path, 3.5.2. |
| d | Demagnified object motion, that is, distance between a speckles from first and second exposures at the image plane (mm), 2.2.1. |
| $\mathbf{d} = [d_1 \quad d_2]$ | The two components of distance moved by a point at the image plane (mm), 4.2.1. |
| D | Diameter of recording aperture (mm), 2.2.3. |
| D_L | Diameter of interrogating laser beam, 2.2.3. |
| D_N | Density of an exposed negative, 3.4.7. |
| e | Axial separation of two speckle planes in optical filtering arrangement (mm), 2.4.1. |
| $e(\mathbf{x})$ | Two dimensional exposure distribution given to emulsion, 3.4.7. |
| E | Exposure given to emulsion, 3.4.7. |
| f | Spatial frequency of speckle in the image (line pairs/mm), 2.2.1. |
| $f(\mathbf{y})$ | Intensity distribution at the object plane, 3.4.2. |
| $\mathbf{f} = [f_1 \quad f_2]$ | Two dimensional spatial frequencies at the image plane, 3.4.2. |
| F | f /number of recording aperture, 2.2.1. |
| $F(\mathbf{f})$ | Spectrum of the object surface, that is, the Fourier transform of $f(\mathbf{y})$, 3.4.2. |
| $g(\mathbf{x})$ | Intensity distribution at the image plane, 3.4.2. |
| $h(\mathbf{u})$ | Intensity distribution at the Fourier plane, 4.2.1. |
| $h_o(\mathbf{u})$ | Intensity distribution of the autocorrelation halo at the Fourier plane, 3.4.2. |
| i | Angular radius of the first bright fringe resulting from axial separation of speckle planes in optical filtering arrangement (rad), 2.4.1. |
| I | Intensity of light falling on emulsion, 3.4.7. |
| I_{\min}, I_{\max} | Minimum and maximum intensities of diffraction fringes, 3.3.1. |
| $k(\mathbf{x})$ | Lens amplitude impulse response, 3.4.2. |
| $K(\mathbf{f})$ | Coherent transfer function, 3.4.2. |
| L | Distance between the negative and the Fourier plane in the optical filtering arrangement (mm), 2.2.1. |
| M | Photographic magnification from object to image plane, 2.2.1. |
| n | Index of refraction of material, 2.4.1. |
| N | Fringe order at the Fourier plane, 2.4.1. |
| p | Object distance, that is, distance from recording lens plane to parallel plane in which the object point lies (m), 3.2.1. |
| $P(\mathbf{r})$ | Recording aperture function, 3.4.2. |
| $P'(\mathbf{r})$ | Aperture function modified to include lens aberrations, 3.4.4. |
| $P''(\mathbf{r})$ | Aperture function modified to include the effects of atmosphere along the optical path, 3.5.1. |
| q | Focal length of recording lens (mm), 2.2.3. |

| | |
|--------------------------------|--|
| $Q(\mathbf{f})$ | Optical transfer function, 3.4.2. |
| r_o | Atmospheric coherence diameter (Fried's parameter), similar to a diffraction limited 'aperture' of the atmosphere (mm), 3.5.1. |
| $\mathbf{r} = [r_1 \quad r_2]$ | Spatial coordinates of the aperture plane, 3.4.1. |
| R | Resolution at the image plane (line pairs/mm), 2.3.2. |
| s | Distance moved by a point on the object (mm), 2.2.1. |
| S | Diffraction fringe spacing (mm), 2.2.1. |
| $\mathbf{u} = [u_1 \quad u_2]$ | Spatial coordinates of the Fourier plane, 3.4.2. |
| $t(\mathbf{x})$ | Amplitude transmittance of negative, 3.4.7. |
| T | Time length of exposure (s), 3.4.7. |
| V | Fringe visibility, 3.3.1. |
| $W(\mathbf{r})$ | Aberration function, 3.4.4. |
| $\mathbf{x} = [x_1 \quad x_2]$ | Spatial coordinates of the image plane, 3.4.2. |
| $\mathbf{y} = [y_1 \quad y_2]$ | Spatial coordinates of the object plane, 3.4.2. |
| Δ | Path difference of interrogating light due to axially separated speckle planes in optical filtering arrangement (mm), 2.4.1. |
| γ | Gamma value of emulsion, that is, a measure of contrast, 3.4.7. |
| λ | Wavelength of light used for optical filtering (nm), 2.2.1. |
| λ_o | Wavelength of light illuminating the object surface (nm), 2.2.1. |
| ρ | Correlation coefficient in digital pattern matching, 4.3.3. |
| σ_i | Speckle diameter at the image plane (mm), 2.2.3. |
| σ_o | Speckle diameter on the object surface (mm), 3.2.1. |
| σ_s | Diameter of secondary speckle (mm), 2.2.3. |
| $\tau(\mathbf{f})$ | Modulation transfer function, 3.4.2. |
| $\tau_o(\mathbf{f})$ | Modulation transfer function of the diffraction limited lens only, 3.4.2. |
| $a \otimes b$ | Convolution of a and b , 3.4.2. |
| a^* | Complex conjugate of a , 3.4.2. |
| $\mathfrak{F}\{ \}$ | Fourier transform, 3.4.2. |
| $\langle \rangle$ | Ensemble average, or expected value, of a random function, 3.4.2. |
| $ $ | Modulus, 3.4.2. |