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Surface evaluation of carbon fibre composites using wavelet texture analysis

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ABSTRACT

Strong and lightweight fibre reinforced polymeric composites now dominate the aerospace, marine and low-volume automotive sectors. The surface finish on exterior composite panels is of critical importance for customer satisfaction. This paper describes the application of wavelet texture analysis (WTA) to the task of automatically classifying the surface finish of Carbon Fibre Reinforced Plastic (CFRP) samples into two quality grades. Automatic classification was successful for all but four samples out of 14,400 classification trial configurations, representing 403,200 sample classification attempts (28 attempts per configuration). This work establishes the principle of WTA as a basis for automatic surface finish classification of composite materials.

1. Introduction

Strong and lightweight fibre reinforced polymeric composites (for example, Glass-Fibre Reinforced Plastic (GRP), and Carbon Fibre Reinforced Plastics (CFRPs)) now dominate the aerospace, marine and low-volume automotive sectors. More recently, environmentally-friendly fibre reinforced composites based on natural fibres and bio-based resins are also finding favour. The mechanical properties of advanced composites are essential for their structural performance, but the surface finish on exterior composite panels is of critical importance for customer satisfaction [1]. Customers demand a flawless (Class A) surface finish, but this can be difficult to achieve on composite surfaces. Dry spots can occur in wet lay-up processes, and the strong reinforcement fibres can 'read through' to the exterior surface, spoiling the cosmetic appearance [2]. While it important that there is further research into materials and manufacturing process to improve surface finish [3], it is essential that composite manufacturers have reliable and repeatable methods for evaluating surface texture. To date, assessment of surface finish quality has tended to be based simply on human visual observation. While this method has been found to deliver results that are acceptable to customers, it is generally performed using several observers in order to produce statistically meaningful results [4], and is therefore time-consuming and not directly adaptable to the automated manufacture of composite products [5].

Systems for the objective assessment of surface quality do exist – divided into two categories: contact measurement (generally employing a stylus used to trace a profile of the surface under examination) and non-contact measurement (generally employing optical sensors to capture an image of the surface under examination that is then processed by computer). Both types of system are capable of accurate measurement of specific surface parameters, but currently struggle to replicate the human visual assessment of surface finish [5], and commercially available systems (for example, the BYK-Gardner Wave Scan DOI instrument is used to assess surface finish [6]) are typically very expensive. A non-contact computer vision system has been demonstrated in a reinforced polymer composite manufacturing application to provide good results in evaluating standard surface roughness parameters [7].

It has been observed that many types of engineering surfaces contain textural features at multiple scales [8], and may be fractal (self-similar at different scales) in nature [9,10]. While there exist a number a numerical methods for characterising engineering surfaces, many require that the distribution of surface features is stationary (i.e., the frequency content does not vary with location), an assumption that is often not valid [8]. It has been shown that the wavelet transform has the ability to effectively characterise surface profile data that contain multi-scale features and are non-stationary [8], and are fractal in nature [9]. For the comprehensive characterisation of surface features and texture, these inherent abilities of the wavelet transform place "it way ahead of other traditional methods" [11], and are why it is "generally considered to be state of the art in texture analysis" [12].

Wavelet analysis has been applied to the characterisation of material surface parameters. Data from 2D wavelet multiresolution analysis were used as the basis for a successful empirical parametric mapping between material surface images obtained via computer vision acquisition and standard surface roughness

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parameters obtained using conventional stylus measurement [13]. In a study to enhance the surface roughness of polymeric filtration membranes via plasma treatment, a wavelet-based characterisation of surface roughness data was used to establish the optimal plasma treatment duration, and was found to provide a more complete characterisation of surface roughness than standard measures [11]. For the objective assessment of surface features of textiles, wavelet-based analysis of computer vision data was shown to be able to distinguish surface imperfections from the underlying fabric weave [14], and more generally to be able effectively characterise fabric surface texture [15].

Wavelet analysis has also been applied to the analysis of surface characteristics of reinforced polymer composites. The utility of wavelet analysis of eddy current sensor data for the identification of surface defects in CFRP composite materials has been demonstrated [16]. Wavelet techniques have been used to analyse surface data to characterise and understand the hydrophobic characteristics of epoxy nanocomposite surfaces [17]. Wavelet analysis has also been used more widely in the identification and characterisation of internal defects in reinforced polymer composites [18,19].

It has been observed that for resin transfer moulded composite plates with surfaces that have approximately similar quality, human visual observation generally outperforms objective (mathematical) methods in the differentiation of sample surface quality – possibly because the standard surface roughness parameters commonly used may not provide an unambiguous indicator of surface quality that agrees with human visual assessment [5]. Direct measurements of standard surface roughness parameters yields only height information about the morphology of a surface and not a total characterisation of a surface [11]. The desirability of objective techniques for the characterisation of surface quality of reinforced polymer composites that can provide the same results as a human subjective evaluation is noted [5].

Physiological experiments have shown that the visual cortex appears to perform a 2D multi-scale decomposition of the visual field into a range of frequency bands/channels [20]. There is considerable similarity between the wavelet transform and biological visual systems. This similarity has resulted in its use in biologically inspired computer vision systems [21]. The 2D wavelet transform is a mathematically robust analysis tool for the characterisation of material surface finish data in ways analogous to human visual processes, and offers practical and rigorous methods for the objective classification of surface quality. This paper demonstrates the application of wavelet texture analysis methods to the task of automatically classifying the surface finish properties of CFRP samples into two quality grades. We seek to establish the feasibility of this approach as the basis for automated non-contact classification of composite surface finish using image analysis methods analogous to the functioning of the human vision system.

2. Material and methods

To assess the feasibility of wavelet texture analysis for objective assessment of composite surface finish, two CFRP sample panels (150 mm × 150 mm) were created. The CFRP panels comprised two layers of 200 g/m^2 carbon fibre plain weave cloth (supplied by ATL Composites – code ZP200) impregnated with epoxy resin (R180 epoxy resin and epoxy hardener H180 standard – supplied by Fibre Glass International, FGI). The carbon fibre cloth was placed on a pre-released flat glass mould surface and resin and hardener mix was introduced by hand using brushes. The panels were backed with a plywood base for flexural stiffness and then vacuum bagged. To create two different surface finishes ('good' and 'bad'), the carbon fibre cloth on the 'bad' panel was not fully wet-out. Insufficient resin resulted in dry areas that were clearly evident at the intersection/cross-over between the warp and weft of the weave. A significantly better finish (less dry spots) could be observed on the 'good' panel when compared to the 'bad' panel. Curing occurred under atmospheric conditions. We purposefully elected to use an un-coated composite in the work presented here; the combination of the visible textile weave construction and the surface finish properties presents a more challenging image analysis/classification task for the proposed WTA method than a coated surface, which removes/hides the potentially confounding visual element of the weave structure.

The two sample panels were scanned at 600 pixels per inch (approximately 236 pixels per cm) using a Hewlett–Packard HP3200C flatbed scanner to yield high resolution 8 bit (256 grey scale) images. These high resolution scans where then separated into 16 sections each with some overlap, yielding 32 sample images – 16 each of good and bad. All numerical analyses described hereafter was performed using the Matlab computing environment [22]. The wavelet analysis method is expedited by images that have linear dimensions of an integer power of two. To this end, all 32 sample images were sized to be 1024 by 1024 pixels for testing. Figs. 1 and 2 show typical 'good' and 'bad' sample test images produced in this manner.

Fig. 3 shows a typical horizontal data cross section from a 'good' sample. Higher data values represent lighter (whiter) elements in the sample image. The fibre plain weave 'under and over' warp and weft structure is readily apparent. Fig. 4 shows a typical horizontal data cross section from a 'bad' sample. The same basic weave structure is apparent in the data, but overlaid on this, at points in the horizontal cross section, are extreme (both high and low) pixel values caused by the dry spots on the bad panels.

Detailed mathematical treatments of the wavelet transform are available elsewhere [23], but, in principle [24], the one-dimensional continuous wavelet transform (1DCWT) involves the comparison of a small waveform (wavelet – a time-limited waveform with particular mathematical properties) with a section of the data under test. The process produces a coefficient that represents the 'match' between the data and the wavelet. The wavelet is translated by a small distance, and the comparison is repeated, in this way, the 1DCWT provides characteristic information about the data that is localised in position. Then, the wavelet is dilated (scaled up) and the process is repeated over a range of scales. Each

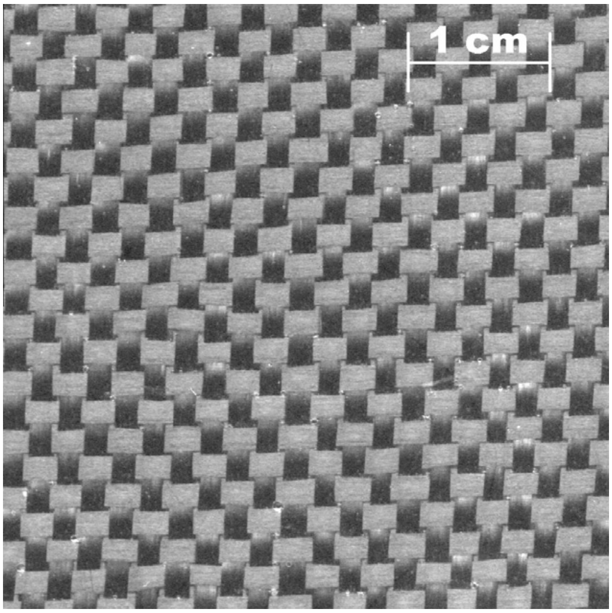

Fig. 1. A typical 'good' sample.