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Measurement of Staple Crimp Frequency.
Part 2: The Crimp Meter – Description.

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SUMMARY

AWTA Ltd has developed a Crimp Meter for the measurement of Staple Crimp Frequency. The device is an addition to the ATLAS machine, with the Crimp Frequency Measurement being conducted concurrently with other staple measurements.

Calibration, Image Capture, Image Processing and Image Analysis details are described.

Tuning the Image Analysis algorithms utilised information obtained using three alternative methods (Manual FFT Peak Determination, Crimp Count By Vision Software, and CSIRO Crimp Gauge measurements).

A preliminary Acceptance Test of the Crimp Meter was successful and further work has been conducted, (reported in part 3) to demonstrate the viability of the system.

INTRODUCTION

This is Part 2 in a series of 3 papers examining the measurement of Staple Crimp Frequency. Part 1 reports precision data for measurements using the CSIRO Crimp Gauge [1]. Part 2 describes a new development, the "AWTA Ltd Crimp Meter". In Part 3, the performance of the Crimp Meter is compared to the CSIRO Crimp Gauge [2].

Staple Crimp

Staple Crimp refers to the generally regular, or wavy, pattern of ripples along the staple. Historically, there have been many ways of describing elements of staple crimp and fibre crimp and measuring or modelling those elements.

If it is assumed that fibre direction in a staple varies in only two dimensions, and that the waviness has a characteristic shape (say a sinusoid), the crimp can be described by the period and amplitude of the ripples [3, 4]. These have been referred to in terms of Staple Crimp Frequency, crimp "depth", and perhaps indirectly as the clarity of the crimp (e.g. "Crimp Definition", "boldness", "character", "uniformity" and "irregularity") [5, 6, 7, 8, 9].

Real-world examples vary greatly from this idealised staple.

Several ways of reporting Crimp Frequency have been used in the past [4, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. This paper shall report crimps per centimetre, with the denominator based upon the natural, unextended length of the staple (the SI units of the measurement are cm^{-1}).

Subjective appraisal of Staple Crimp Frequency as an estimator of Fineness formed the basis for fine wool valuation until the adoption of Objective Measurements [4, 10, 20, 21, 22, 23]. Recently there has been renewed commercial and technical interest in Staple Crimp Frequency as a means of differentiation between wool for trading and processing [7, 8, 24, 25, 26, 27, 28]. Staple Crimp Frequency has been shown to be correlated with Fibre Curvature [6, 9, 13, 24, 29, 30, 31].

Staple Crimp Frequency is considered an important factor in the subjective appraisal of Style [20, 28, 32, 33, 34].

The CSIRO Style Instrument

Development of the Style Instrument began in the early 1980's and concluded in 2001 [32]. It incorporated measurement of Staple Crimp Frequency based upon analysing single lines of light intensity data [35], as one of a suite of parameters measured to estimate Wool Style. A comparison of Staple Crimp Frequency measurements between two Style Instruments (with two replicates) produced Standard Error of Slope values of 0.052 and 0.036 for the Geometric Mean, and 0.051 and 0.037 for the Difference vs Average [36]. However, the measurement of other style parameters by this instrument was less satisfactory. For this and other reasons the instrument was deemed unviable in the 2001 commercial environment [32] and the project was suspended.

DEVELOPMENT OF THE AWTA LTD CRIMP METER

Prior to the fabrication of the Crimp Meter prototype, the imaging system and software development activities were carried out using a simpler enclosure, a "Crimp Cabinet" (Figure 1).

304 staples from a range of wool types (including Lambs, Bellies, Cross-Bred, Superfine Merino, Medium Merino and Strong Merino), and covering a wide range of Crimp Frequencies[42] were used in the development.

Figure 1: The Crimp Cabinet

Determination of Crimp Frequency of Reference Staples

Three independent estimates of Crimp Frequency were obtained for comparison with the Crimp Frequency values determined by this development system:

- measurement using the CSIRO Crimp Gauge (the primary reference system);
- estimation by examination of the Staple Images (2 images per staple); and
- estimation by examination of the Fourier Transform produced by the "turnkey" imaging software.

<u>The CSIRO Crimp Gauge</u>

The CSIRO Crimp Gauge is a metal plate edged with a series of saw-tooths covering a range of frequencies. It could be held against a wool staple to help the user estimate the Staple Crimp Frequency (Figure 2).

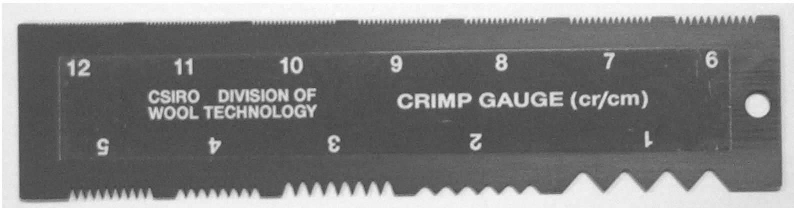

Figure 2: CSIRO Crimp Gauge (not to scale)

This method is the primary reference method and was used during the subsequent testing of the systems when it was transferred to the ATLAS instrument

<u>Crimp Frequency Estimation By Examination Of Staple Images</u>

Information describing the Spatial Domain was obtained by placing an object of known length in the Field of View and recording its image. This permitted the Spatial Domain Calibration Constant (cm.pixel^{-1}) to be determined. The image of a Spatial Domain Calibration Pattern was recorded during pre-measurement checks. For the estimation from the staple image described here, a steel rule was used.

Vision software* was used to examine staple images. This "turnkey" software permitted a "Line of Interest" to be manually overlaid along any part of the staple image. The position of the line was recorded and the crimps along the interval counted. In conjunction with the Spatial Domain Calibration Constant, the Crimp Frequency along the interval was estimated.

<u>Crimp Frequency Estimation By Examination Of The Fourier Transform</u>

The "turnkey" software can also produce a Fourier Transform of the staple images. These data were examined visually to identify noteworthy frequencies.

This was made possible by assigning a colour palette to the magnitudes of the Frequency Domain data to present the magnitudes as an image. This allowed the position of noteworthy features (hence Crimp Frequency and Direction) to be identified manually, and therefore provide a check on the automatic analysis software as it was being developed.

Tuning and Validation

The software uses six sets of constants, with each set covering the range of Crimp Frequencies. Each value was fine-tuned to better line-up the results produced by the automation software against the Crimp Frequency results produced by the 3 methods described above. This was repeated many times and ultimately refined into a process where 204 of the staples were randomly selected to perform fine-tuning, and the remaining 100 were measured as a Validation. The Validation results for each staple were classified using various low-level categories, which could be tallied into the broad groupings of

* e.g. National Instruments' Vision Builder for Automated Inspection

"Accepted", and "Rejected". Typical outcomes for the tuned system were 80% and 20% respectively. The Rejected category included inappropriate selection of very low frequencies or their harmonics, and an inability of the system to isolate a dominant frequency in staples of poor Crimp Definition.

The constants determined at the Crimp Cabinet were later applied to the Crimp Meter without alteration.

THE AWTA LTD CRIMP METER – DESCRIPTION AND OPERATION

Description

The Crimp Meter consists of a near-lightproof enclosure, a light and a camera. The enclosure incorporates doors on each side, and openings for the camera lens and the light source. A staple can be placed into the camera's Field of View by hand. The trial prototype was designed as a simple add-on to ATLAS [37] (Figure 3). The feed belt delivers a staple into the enclosure, where it falls onto the length belt. The camera records an electronic image of the still staple before the length belt transports it out of the enclosure and onward to the optical detection (length measurement) system.

The camera is mounted directly above the length belt. The model used is an 8-bit analogue device producing CCIR[*] square-pixel images (i.e. 768 pixels wide x 576 pixels high). The camera can distinguish 2^8 (i.e. 256) shades of grey, numbered from zero (black) to 255 (white). An image acquisition PC card converts the analogue signal to digital. A captured image thus becomes a two-dimensional array of greyscale values stored on the hard drive of the PC.

A halogen bulb is mounted in the angled panel of the enclosure. The intensity of the light is set as a pre-measurement check, so that the mean greyscale value of a grey Working Tile matches a pre-determined target value. The grey level of each pixel in the staple image is affected by the subject, the intensity of incident light, the aperture setting, focus setting and shutter speed of the camera, and the overall Modulation Transfer Function (MTF) [38, 39] of the system. The MTF includes the contributions of the lens, the Charge-Coupled Device (CCD) and electronics within the camera, the Gain and Contrast ("gamma") settings of the camera, the BNC cable between the camera and the PC, and the image acquisition card (including its Gain and Reference Voltage settings). Although the MTF of each equipment combination varies, successful harmonisation can be achieved by using a consistent set of Working Tiles with appropriate target values.

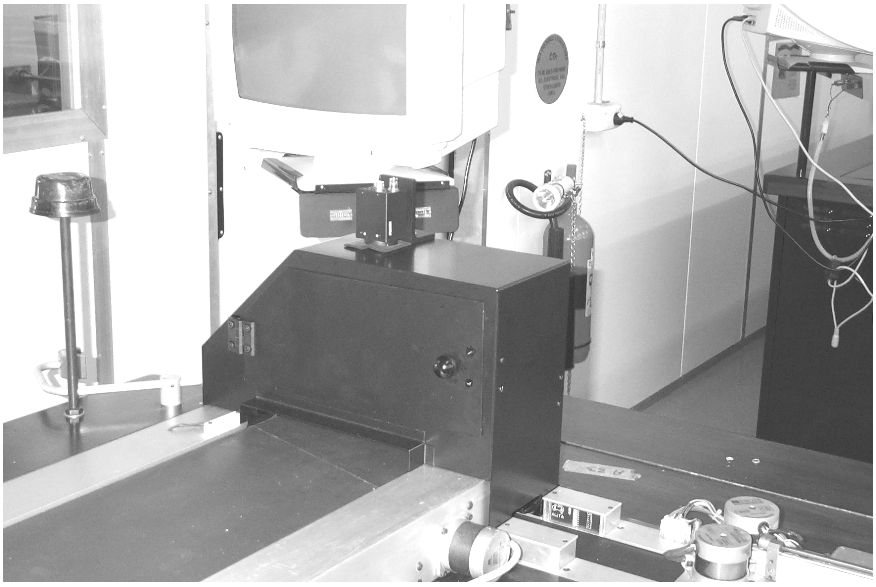

Figure 3: Prototype Crimp Meter mounted on an ATLAS

[*] CCIR ("International Radio Consultative Committee") is now known as the International Telecommunication Union Radiocommunication Sector. The standard is "Recommendation BT.601-5 (10/95). Studio Encoding Parameters of Digital Television for Standard 4:3 and Wide-Screen 16:9 Aspect Ratios".

The combination of Working Distance (between the lens and the length belt) and lens size is selected to provide the best resolution within the normal limits of the camera. This results in a Field of View of 7.1 cm x 5.3 cm. The Crimp Meter measures the portion of the staple within the Field of View. Marker lines on the feed belt aided the operator in positioning the staple so that it lands in the Field of View. The 5 cm wide length belt passes through the middle of the Field of View, with a mounting plate for the feed belt photocells occupying the top of the image. An ATLAS "deflector plate" [#], which sits above the length belt, forms the lower portion of the image. Each surface within the enclosure is black except the feed belt and the length belt, which are green.

Operation

The determination of Staple Crimp Frequency beyond Image Capture involves Instrument Setup, Image Processing and Image Analysis. These three steps are described below.

<u>Instrument Setup</u>

Physical setup is performed as part of the pre-measurement checks. The pattern of concentric circles is used. The frequency of the pattern can be measured by a ruler. The pattern is placed on the length belt and its image recorded.

The two dimensional Fourier Transform of the pattern is a set of concentric circles, with radii representing the pattern's frequency and harmonics of that frequency. The inner circle is easily identified, permitting the calculation of a Frequency Domain Calibration Constant ($cm^{-1}.pixel^{-1}$).

<u>Image Processing</u>

The staple image is prepared for analysis by identifying those pixels forming the background.

Pixel values below a "Lower Threshold" value are set to zero. The computation increments this Lower Threshold greyscale value until key criteria are met - i.e. the area occupied by the staple and the average greyscale value of the staple are within certain limits, and only one object is present in the image. On rare occasions, the latter might not be achieved - usually due to dark zones across the staple. Such images are rejected. When the conditions are satisfied, the zero pixels are replaced with an integer value nearest the mean of the staple.

<u>Image Analysis</u>

A Fourier Transform across two dimensions is carried out on the array of greyscale values representing the staple image (with a uniform background). This produces a same-sized array of complex numbers. Both magnitude and phase data are retained to invert this Frequency Domain array back to the Spatial Domain [40]. However, useful Frequency Domain information can be determined by discarding the phase data and dealing only with magnitudes.

For convenience, the Frequency Domain array is translated so that the zero-frequency element is central to the array of magnitudes, and the rest of the data is symmetrical around the i = j diagonal (where i is the row and j the column). In signal processing, the zero frequency is referred to as the "DC component".

The two dimensional array can be visualised as a mountain range [41], with the altitude representing Frequency Domain magnitudes and the map co-ordinates representing rows and columns. Each element records something about the image, and the analysis task is to determine which peaks are sufficiently noteworthy. The distance[*] between the location of those peaks and the central pixel represents their frequencies, whilst their direction from the centre matches the normal to the feature that they represent (eg crimps).

[#] The "deflector plate" prevents staples from rolling off the length belt after dropping from the feed belt.

[*] The fact that a rectangular image is used means that directions and distances in the Frequency Domain are not straightforwardly translatable. For example, the Fourier Transform of concentric circles will actually be concentric ellipses with the minor axis being 576/768 (=3/4) of the major axis. When frequencies and directions represented by features of the Fourier Transform in the Frequency Domain are calculated, this effect must be taken into account. Discussion of frequencies and directions throughout this paper presumes that the adjustment has been performed.

Two algorithms are used to report peaks. Both incorporated sets of constants to determine whether a peak is noteworthy relative to its neighbours, and to check if it might really be the second or third harmonic of another peak. The zone of frequencies considered is bound by upper and lower limits, and the direction by maximum and minimum angles from the horizontal.

Mathematical rules were developed to determine whether one or two noteworthy frequencies ought to be reported for the staple. (Some staples were observed to have distinctly different Crimp Frequencies at each end, and both could be identified). Sometimes the two methods returned outcomes that disagreed, and sometimes neither could determine a satisfactory peak. In those instances, usually a small proportion of the outcomes, no result was recorded.

The use of a two dimensional Fourier Transform means that the orientation of the staple on the belt can vary slightly – a necessary capability if the device is to be fitted to an operational ATLAS instrument.

Acceptance Testing Of The Crimp Meter

A procedure was developed to determine whether a combination of Crimp Meter, ATLAS, light, camera, lens, BNC cable and image acquisition card could be deemed “Accepted” for testing staples. The first stage involved physical checks of the equipment, checking the camera and light alignment and recording Identification Numbers of each item of equipment. The second stage was a Validation using 100 staples randomly selected from the 304 originally used to develop the software. The Accepted:Rejected ratio needed to be consistent with previous outcomes for the Acceptance Test to pass.

An Acceptance Test of a prototype Crimp Meter positioned on a commercial ATLAS proved successful. The Accepted:Rejected outcome was 77:23.

The Acceptance Test pass permitted the commencement of the Performance Trial reported in Part 3 [2].

DISCUSSION

Lighting Level In The Crimp Meter Enclosure

Over the short term, the illumination provided depended strictly upon the DC voltage supplied to the bulb, and hence the capabilities of the power supply used. The voltage was approximately 2.9 V. A ripple of ±0.01 V was observed with a period of 12.5 nanoseconds. Although this amplitude would translate to approximately ±0.7 greyscale units for the Working Tile, the period is tiny compared to the shutter time (1/60th of a second) and the ripple would have no effect.

The illumination drift over the course of a measurement session, although not formally monitored, appeared to be less than 1 greyscale unit (as measured using the grey Working Tile). Tight voltage control of the DC power supplies used in a commercial implementation would reduce the required frequency of Working Tile checks.

Implications Of The Frequency Calibration Constant

The Frequency Domain calibration pattern was assessed to be 4.035 cm^{-1} (i.e. 23 cycles @ 5.70 cm). The single-point calibration returned a calibration constant of 0.144 $cm^{-1}.pixel^{-1}$.

This leads to two matters of interest. The Frequency Domain peak for this determination was 28 pixels from the FFT centre. Hence the inherent imprecision of the calibration due to pixellation is ±(½ x 1/28 x 100%) = ± 1.8 %. This could be improved by using a higher frequency pattern or multiple patterns. Secondly, in measuring the FFT of a staple image with vertically-aligned crimp, the difference between an element and its neighbour represents 0.144 $cm^{-1}.pixel^{-1}$, confirming that individual Crimp Meter measurements should not be reported to more than one decimal place.

CONCLUSION

A Crimp Meter has been developed and appropriate software produced. The device can be mounted on an ATLAS instrument so that Crimp Frequency measurements can be conducted during the normal operating cycle of the instrument, utilising the same staples prepared for Staple Length & Strength. Successful operation relies on the setup of the camera and the stability of the light source.

The Crimp Meter is considered robust enough for further evaluation. The performance of the device measuring a different set of greasy staples is reported in Part 3 [2].

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