Surface texture assessment by statistical analysis of optical Fourier transform patterns.

Lawrence Cuthbert
University of Windsor

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SURFACE TEXTURE ASSESSMENT BY STATISTICAL ANALYSIS
OF OPTICAL FOURIER TRANSFORM PATTERNS

by

LAWRENCE CUTHBERT

A Thesis
Submitted to
the Faculty of Graduate Studies and Research
Through
the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at
the University of Windsor

Windsor, Ontario, Canada

1991
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ABSTRACT

The object of this research was to develop an optical method for surface texture assessment. The optical method involves a statistical analysis of optical Fourier transform patterns.

The technique involves the use of a He-Ne laser to illuminate a rough surface. The optical Fourier transform pattern is then focused onto a CCD camera, digitized and captured by a digitizer and frame grabber board. The digitized image is fed into a micro-computer for analysis.

Analysis of the optical Fourier pattern involves the determination of the grey-level intensity histogram of the pattern. From this histogram several statistical parameters were determined and correlated with the surface roughness. However it was found that an optical parameter \( R_{\text{standard deviation}} \) produced the best results. \( R \) was correlated with surface roughness for surfaces of different materials that were produced by different machining processes. It was found that a useful correlation existed between \( R \) and surface roughness for fairly smooth surfaces with \( Ra \) values less than about 0.8\( \mu \)m.

The effect of surface flaws on this technique was also investigated. It was found that when a flaw was present, there was a significant reduction in the \( R \) value. This method may be used in this fashion to detect flaws.

This technique provides a fast non-contact method of
surface texture assessment. The statistical analysis of the optical Fourier transform pattern allows the pattern to be used to assess texture of two dimensional as well as one dimensional surfaces.
Dedicated with love to my parents  
Dr. Marlene Cuthbert  
and  
the late Rev. Dr. Robert Cuthbert
ACKNOWLEDGMENTS

I would like to express my sincere thanks to Dr. V.M. Huynh for his patience and guidance throughout my masters studies. I would also like to thank Dr. W. North and Dr. J. Soltis for their help and assistance.

I am grateful to Mr. Satya Kurada for his invaluable advice and encouragement. In addition I would like to thank Sandrena Phillip, Kent Cuthbert and my mother, Marlene Cuthbert who all helped motivate and inspire me when I most needed it.

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LIST OF ABBREVIATIONS

a = Slit width
\( a_o, a_n \) = Fourier coefficients
\( A_o \) = Maximum amplitude
\( \alpha \) = Angle of incidence
\( \alpha_s \) = Skew
\( \alpha_k \) = Kurtosis
\( b_n \) = Fourier coefficient
\( C_n \) = Fourier coefficient
\( \Delta l_1 \) = A small distance
\( \Delta l_2 \) = A small distance
\( E_i \) = Amplitude of the i'th source
\( E_o \) = Maximum electric field amplitude
\( E_r \) = Resultant electric field amplitude
\( E_T \) = Total source electric field amplitude
\( E(t) \) = Time varying electric field amplitude
\( E(\theta) \) = Electric field amplitude as a function of \( \theta \)
\( f(x) \) = Periodic function
\( f_i \) = Number of pixels at grey-level i
\( g(x) \) = 1-periodic function
\( G(u) \) = Fourier transform of \( g(x) \)
\( \gamma(x) \) = Phase modulation function
\( h(x) \) = Surface profile function
\( i \) = An integer
\( \frac{I_i}{I_0} \) = Normalized intensity at point i
\( I(r) \) = Light intensity at point r
\( I_T \) = Total source intensity

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\( i(\theta) \) = Light intensity
\( j \) = \( \sqrt{-1} \)
\( k \) = Wave number (2\( \pi /\lambda \))
\( K \) = Normalization factor
\( L \) = Assessment length
\( \lambda \) = Wavelength of light
\( \Lambda \) = Wavelength of a periodic profile
\( \mu \) = Mean
\( n \) = An integer
\( N \) = A large number
\( \omega \) = Angular frequency
\( \omega_0 \) = Fundamental frequency of \( f(x) \)
\( P(u) \) = Fourier transform of \( p(x) \)
\( p(x) \) = Reflected wavefront function as a function of \( x \)
\( p(x,t) \) = Reflected wavefront function as a function of \( x \) and \( t \)
\( \phi \) = Phase difference
\( \delta \) = Total phase difference
\( r \) = A radius
\( R \) = Optical roughness parameter (SD/RMS)
\( R_{a} \) = Mean surface roughness
\( R_{f} \) = Fringe contrast ratio
\( \text{RMS} \) = Root mean square
\( R_{q} \) = Root mean square surface roughness
\( R_{y} \) = Maximum peak to valley surface height
\( \rho \) = Ratio of reflectivities
\( \text{SD} \) = Standard deviation
\( S_{N} \) = Weighted quadratic mean value of the intensity
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CHAPTER I
INTRODUCTION

Assessment of surface texture is becoming increasingly important in many fields of science and engineering. Such things as corrosion resistance, the probability of fatigue crack formation and the effectiveness of lubrication in moving parts are affected by surface roughness. Furthermore, the demand of the manufacturing industry for high dimensional tolerances, and 100% inspection of critical parts continues to grow. For these reasons, there is a greater need for non-destructive, high speed methods of surface texture determination.

On-line, in-process monitoring of surface texture is important due to the fact that a small increase in the quality of a surface finish will result in a large increase in manufacturing costs. Therefore, if the quality exceeds the required specifications, then a large amount of money is wasted. Moreover, if a manufactured surface does not meet the required specifications, then the whole production series may have to be rejected.

The measurement and analysis of surface texture of machined parts can also be an excellent diagnostic tool for monitoring the machining process. If such monitoring is implemented then it is possible to use the machining tool to the end of its useful life and replace it as soon as it ceases to be functional. This again results in a reduction
in production costs.

1.1 Surface texture

According to the American National Standards Institute [1], surface texture is the repetitive or random deviations from the nominal surface which form the three dimensional topography of the surface. There are several terms used in the description of surface texture; these are illustrated in Figure 1.1 and defined here:

a) Roughness: This includes the smaller, finely spaced irregularities of the surface texture. These irregularities are usually as a result of the inherent action of the production process. The most commonly used parameters to characterize roughness are Ra and Rq (rms roughness). Ra is the arithmetic mean of the absolute value of the surface variations from the mean line, i.e.:

\[ Ra = \frac{1}{L} \int_{0}^{L} |y(x)| \, dx \]

where:

\[ y(x) = \text{The surface profile along the x direction}. \]
\[ L = \text{The assessment length}. \]

Rq, on the other hand, is the square root of the mean of the surface profile squared, i.e.
\[ R_q = \left[ \frac{1}{L} \int_0^L y^2(x) \, dx \right]^{1/2} \]

b) Waviness: This includes the more widely spaced surface features. This may result from machine or work deflections, vibrations, or chatter during machining.

c) Lay: This describes the direction of the predominant surface pattern. It is usually determined by the production method used and it is possible for a surface to have more than one lay direction.

d) Flaws: These are unintentional irregularities that do not occur in any consistent pattern including scratches, dents, cracks, etc.

1.2 Surface texture assessment by the stylus method

The traditional technique for quantitative surface texture evaluation is with the stylus profilometer. With this instrument, measurements are made by tracing the surface with a diamond stylus to produce a time varying voltage which is directly proportional to the surface profile. This instrument produces an accurate one dimensional profile along the traversed direction. From the profile the surface roughness as well as the waviness can be quantified. The extent to which the waviness of the surface can be measured is limited by the distance travelled by the stylus. Meanwhile, the minimum roughness that can be measured with this method is limited by the
radius of the stylus tip.

The stylus instrument has a large range, produces accurate measurements and is the accepted standard for measurement of surface roughness. However, the stylus method has several disadvantages: (i) It is a contact method and can damage the surface under inspection. (ii) The stylus method is generally slow and not suited for on-line or in-process assessment of surfaces. (iii) Depending on the hardness of the surface, the profile obtained from this technique may be misleading if a soft material is used. (iv) The stylus technique only gives a one dimensional profile and information in other dimensions is lost. For example if a surface has more than one lay direction then measurement by the stylus could produce a profile that does not include any information from one of the lay directions. (v) Because of the one dimensional nature of the stylus profile, it is impractical for detection of flaws.

Much work has been done to develop alternate methods of surface texture evaluation to overcome the disadvantages of the stylus technique. Attempts have been made to develop ultrasonic as well as capacitive and inductive methods; however, the most promising approach has been the use of optical techniques to assess surface texture. The present research investigates the use of a statistical analysis of optical Fourier transform patterns for surface texture assessment.
1.3 Objectives

The aim of this research is to assess the surface texture of two dimensional surfaces by using an optical Fourier transform technique. Specifically, this research work pursues the following objectives:

a) To investigate the relationship between surface roughness and statistical parameters obtained from a grey-level histogram of the optical Fourier transform pattern.

b) To utilize the statistical analysis and derive an optical parameter that can be related to the surface roughness.

c) To determine the effect of certain factors on the relation between the optical parameter and surface roughness, namely; the size of the spatial filter, the magnification of the Fourier pattern, and the intensity of the laser light.

d) To obtain correlation curves for the optical parameter versus surface roughness for different materials and machining processes.

e) To determine how the presence of certain flaws affects the optical parameter.

A review of some optical methods for surface texture assessment is given in Chapter II. The theory on which this method is based is presented in Chapter III.
Figure 1.1: Description of surface texture components: roughness, waviness, lay and flaws.
CHAPTER II
LITERATURE SURVEY

Optical methods for surface texture assessment are, by nature, non-contact. These techniques can be very accurate as well as fast. Some optical methods have, in fact, been applied successfully to in-process, on-line surface texture assessment. The examples of optical surface texture assessment techniques reviewed here are interferometry, laser speckle, light scattering and optical Fourier transform techniques.

2.1 Interferometric methods

One optical technique for surface texture evaluation involves the use of interferometry. An interferometer produces interference fringes due to the path difference of a light beam reflected off a reference surface and one reflected off the object surface. In order to use this method to assess surface texture the object surface is replaced by a rough surface. The Michelson interferometer, one of the most basic interferometers, will be used to illustrate the use of this type of technique for surface texture assessment [2,3].

A schematic diagram of the Michelson interferometer is shown in Figure 2.1. The light source is monochromatic, usually a laser. The glass plate P, equal in thickness to
M₁ is placed in the path of the horizontal ray in order to equalize the path lengths of the two rays. With this arrangement, each ray will pass through the same thickness of glass.

If the device is set up as shown in Figure 2.1 a series of light and dark fringes will be observed on the screen. Optically, the system consists of two sources M₁ and M₂ one behind the other. The path difference between these sources results in the formation of interference fringes at infinity. With this configuration the displacement of M₁ in the direction perpendicular to its plane can be measured with an accuracy of better than the wavelength of the light source.

To measure surface roughness the mirror M₁ in Figure 2.1 is replaced with a test surface. The fringes will become "fuzzy" due to the surface roughness of the test surface and this can be measured with the fringe contrast ratio. The fringe contrast ratio of the interference pattern will be determined by the mutual coherence of the two wave fronts. Therefore, assuming that the light source is perfectly monochromatic, and that the reference mirror is practically smooth compared to the test surface, then the roughness of the surface determines the mutual coherence of the two wavefronts.

The fringe contrast ratio is the ratio of the maximum light intensity to the minimum light intensity. To derive a mathematical expression for the fringe contrast ratio, it
is assumed that the incident light is approximately normal to the test surface, and shadowing can be neglected. This will be valid for relatively smooth surfaces whose roughness is much less than the illumination wavelength.

The fringe contrast ratio, \( R_f \), is given by:

\[
R_f = \left[ \frac{\rho + \exp(-k^2\sigma^2/2)}{\rho - \exp(-k^2\sigma^2/2)} \right]^2 \tag{2.1}
\]

Where \( R_f \) = The fringe contrast ratio.
\( \rho \) = The ratio of reflectivities of the reference and test surfaces.
\( k = 2\pi/\lambda \) (\( \lambda \) = The wavelength of the light source).
\( \sigma \) = The RMS roughness of the test surface.

This is for surfaces having a Gaussian height distribution, and when the optical distances from the reference surface and the test surface to the image plane are approximately equal. From the above expression, the RMS roughness is given by:

\[
k\sigma = 1/2 \ln \left[ \frac{(R_f+1)^{4/2}}{\rho (R_f-1)^{4/2}} \right] \tag{2.2}
\]

This means that the RMS roughness of the surface can be determined from the fringe contrast ratio, which can be measured directly.

Other forms of interferometry can be used to determine roughness [4-6]. These include using oblique incidence
interferometry [4], heterodyne interferometry [5] and holographic interferometry [6]. Interferometric methods have been used in commercially available instruments to measure surface roughness [7]. All interferometric methods are based on the same basic principles and have the following limitations: The lowest roughnesses that can be measured using these techniques is limited by the maximum fringe contrast ratio obtainable for the configuration. This is determined by the quality of the reference mirror and the coherence of the laser. On the other hand, the maximum roughness that can be measured using this method is determined by the wavelength of the light used, that is, the roughness of the surface must be small compared with the wavelength of the light source so that the diffraction model is valid. These methods have been used to accurately measure roughnesses on smooth surfaces generally with Ra of the order 0.1μm or less.

2.2 Laser speckle

Another optical method of surface texture assessment is laser speckle [8,9]. This technique utilizes the phenomena of speckle which is produced when a rough surface is illuminated with coherent or partially coherent light. This random pattern consists of bright and dark regions as shown in Figure 2.2. It is a diffraction phenomenon that can be explained using Huygen’s principle. Similar to
single slit diffraction, speckle can occur in both the near field (Fresnel plane) or the far field (Fraunhofer plane).

Figure 2.3 shows an experimental set up used for the assessment of surface texture using the laser speckle method [8]. With this arrangement, the laser beam reflected once by the mirror M and expanded by an inverted telescope L_x was used to illuminate an aperture P_1. The light transmitted through the aperture was converged by the lens L_o onto its focal plane P_2 where a very small light spot was formed. The sample was moved across the illuminated light spot. This produced a varying speckle pattern in the far-field. The intensity variation was detected by a photomultiplier P_m with a pinhole P_s fixed at the center of the far-field diffraction plane P_s of the illuminated object surface area and was made smaller than the average grain size of speckle patterns. The photomultiplier signal current was fed into a signal-analyzing system in order to calculate speckle contrast. The speckle contrast was then used to determine the surface roughness.

Speckle contrast is defined as the normalized standard deviation of intensity variations at the image plane and can be expressed as:

\[ V = \frac{[\langle I^2(r) \rangle - \langle I(r) \rangle^2]}{\langle I(r) \rangle} \]  \hspace{1cm} (2.3)

Where \( V \) = The speckle contrast.
I(r) = The intensity of the image at point r.

As increasing roughness decreases the degree of coherence of the reflected light, the speckle contrast decreases as the surface roughness increases. A calibration curve is normally obtained for use in the determination of roughness by this method. As this curve is dependent on the material and machining process, a different calibration curve may be required for any given application.

Another approach is to use the correlation between two speckle patterns from the same surface to assess surface texture. In this case the two speckle patterns are obtained from the test surface by using different angles of incidence or different wavelengths of light. The patterns are then compared by determining a cross-correlation function. This cross-correlation function can then be correlated with surface roughness.

Several studies [8,9] have been carried out to investigate the use of laser speckle methods to assess surface texture with some success. It has been found that the minimum roughness for which laser speckle methods are applicable is limited by the coherence of the laser light and the resolution of the equipment used. The maximum roughness obtained by these methods is limited by the illumination wavelength, that is, the roughness must be small compared with the wavelength. In practice these techniques have been used to measure roughnesses of fairly
smooth surfaces with Ra values in the order of micrometers or less.

2.3 Light scattering

The majority of non-contact techniques for surface texture assessment are based on some form of light scattering. Work in this area has resulted in the development of some commercially available devices that are used for the on-line and in-process assessment of surface roughness.

When light is reflected off a rough reflective surface it will be scattered as represented in Figure 2.4. The scattered light consists of a specular portion and a diffuse portion. The specular portion is the light that is reflected in the direction defined according to Snell's law. On the other hand, the diffuse portion is the portion that is scattered in all other directions.

If the surface height variations are much larger than the wavelength of the illuminating light then the angular distribution of the scattered light is determined by geometric optics where light is reflected according to Snells' law. However, if the surface height variations are much smaller than the wavelength of the light, then the light will be diffracted and information about the angular distribution of the light can be predicted using a diffraction model. Beckmann and Spizzichino [10] have
proposed a basic theory for predicting the behavior of light scattering from rough surfaces. However, to date, all the scattering theories rely on only geometric optics or diffraction theory to make predictions about the angular distribution of the scattering pattern. As a result, optical surface texture assessment methods that use scattering usually employ a model which assumes that the surface height variations are very small, or large compared with the illumination wavelength [14,15]. Apart from these methods, other techniques based on an empirical approach have also been developed [12,16].

Surface texture assessment can be accomplished by measuring some features of the angular distribution of the scattering pattern and relating this to surface texture. One method is to measure the specular intensity of the reflected beam [11,12] which can be correlated with the RMS roughness of the surface. A commercially available device, known as the Compari-Surf [12], measures the specular intensity and produces a reading from 0 to 100. Calibration is necessary using standard surfaces of the same material produced from the same machining process. As such, this device is useful only as a comparator.

On the other hand, it is possible to measure the intensity of all but the specular light. This is known as the method of total integrated scatter [13,14]. With both the specular and the total integrated scatter methods it is possible to develop a theoretical expression relating the
RMS roughness of the surface to the measured intensity.

Another approach is to use the entire angular distribution to calculate some parameter that relates to surface roughness [15,16]. Using this approach it is possible to develop a variety of theoretical relationships between the angular distribution scattering patterns and the roughness of the surface. One commercially available instrument, the RM 400 [16], uses this technique to measure surface roughness by determining the weighted quadratic mean value of the intensity distribution ($S_N$). This can be expressed mathematically as follows:

$$S_N = K \sum_i (\theta_i - \bar{\theta}_i)^2 \frac{I_i}{I_o} \quad \ldots (2.4)$$

Where $K$ = A normalization factor.

$i$ = A point in the observation plane.

$\theta_i$ = The scattering angle to point $i$.

$\bar{\theta}_i$ = The mean value of the scattering angle.

$\frac{I_i}{I_o}$ = The normalized intensity at point $i$.

This device operates by measuring $S_N$ which can then be related to roughness using a calibration curve. It is therefore used empirically as a comparator. A schematic diagram of this instrument, the RM 400, is shown in Figure 2.5a, while Figure 2.5b shows the device being used in process to measure the roughness of ball pins. Some features of the RM 400 are given in table 2.1 below.
<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring range:</td>
<td>depending on machining</td>
</tr>
<tr>
<td></td>
<td>(0.005 \mu m &lt; \text{Ra} &lt; 2 \mu m)</td>
</tr>
<tr>
<td>Measuring time:</td>
<td>(&lt;50\text{ms})</td>
</tr>
<tr>
<td>Measuring area:</td>
<td>max. diameter 5mm</td>
</tr>
<tr>
<td></td>
<td>min. diameter (0.1\text{mm})</td>
</tr>
<tr>
<td>Measuring error:</td>
<td>(&lt;2%)</td>
</tr>
<tr>
<td>Measuring dist.:</td>
<td>Max. 20mm, tolerance:</td>
</tr>
<tr>
<td></td>
<td>distance (\pm 2\text{mm}) tilt (\pm 2^\circ)</td>
</tr>
<tr>
<td>Permitted curvature</td>
<td>Min. curvature radius (\approx 1\text{mm})</td>
</tr>
<tr>
<td>of measuring area:</td>
<td></td>
</tr>
<tr>
<td>Speed of measuring area:</td>
<td>no influence</td>
</tr>
</tbody>
</table>

Table 2.1: Features of roughness tester RM 400 [16].

Another scattering approach is the Fourier transform technique which uses the far field image formed when monochromatic light is reflected off a rough surface. This is discussed in the next section.

2.4 Optical Fourier transforms

The investigation of optical Fourier transforms for surface texture assessment has not yet produced any commercially available devices, but the potential has been demonstrated.
The theoretical description of the Fourier pattern produced by monochromatic light reflecting off a rough surface is dealt with in the next chapter. Using this approach, a good experimental correlation has been found between the theoretical and actual Fourier patterns produced for a variety of surfaces with RMS roughnesses up to about 0.03 times the illumination wavelength ($\lambda$) [17-19]. Some work has also been carried out to investigate the predicted roughness using a Bessel function solution to determine the diffraction pattern formed by light scattering from rough surfaces. Here, a good correlation was established [17] between roughness determined optically and roughness determined mechanically for roughnesses up to about 0.13 times ($\lambda$).

Experimental investigations have also been carried out to correlate the roughness of a surface to parameters derived from the optical Fourier pattern [20-23]. In the work of Kurada [20], a wide variety of surfaces of different materials and machining processes were studied and a good correlation was found between the surface roughness parameter $Ra$ and the amplitude of the normalized Fourier spectrum peak. In addition, a good correlation was found between $Ra$ and the RMS value of the Fourier spectrum. Here, the results were found to be applicable to surfaces with $Ra$ values up to about 0.8 times ($\lambda$).

A larger range was achieved in a study of grinding samples obtained with roughness standards [21], having $Ra$
values of up to about 1.2 times ($\lambda$). In this case a good correlation was found between $R_a$ and three spectrum parameters, namely, the relative intensity of the spectrum peak, the standard deviation of the intensity distribution, and the equivalent spectral energy.

As indicated above, it is possible to assess a wide range of roughnesses using this method. If illumination in the visible spectrum is used, then smooth surfaces with roughnesses in the micrometer range or below can be measured. Above that range, a diffraction model is not valid and empirical relationships must be determined between roughness and spectrum parameters. Generally, this requires a different calibration curve for different machining processes. Another disadvantage with this method, as it has been applied to date, is that the information about the roughness of the surface is taken only from along one direction at a time. For a two dimensional surface, multiple profiles need to be determined which would be impractical.

2.5 Other methods

A variety of other optical methods for surface texture assessment are available. Techniques such as ellipsometry, moire fringe, light sectioning and others have been used to assess surface texture. However, there no clear indication of any one superior method among these. It is likely that
the use of optical methods for surface texture assessment will increase in the years to come and different methods will be used in applications for which they are best suited.

In the next chapter, the theoretical aspect of the optical Fourier transform method used in this study will be described.
Figure 2.1: A schematic diagram of the Michelson Interferometer.
Figure 2.2: Speckle patterns [27]:
a) surface roughness 1.3μm
b) surface roughness 0.2μm
Figure 2.3: Schematic diagram of the apparatus for roughness measurement using speckle [8].
Figure 2.4: Scattering of light from rough surfaces.
Figure 2.5:  a) Schematic diagram of the RM 400 roughness measuring instrument [16].

b) The RM 400 being used for on-line measurement [16].
CHAPTER III
THEORY

The proposed optical surface texture assessment technique employs the optical Fourier transform to produce a diffraction pattern which is subsequently analyzed for surface texture assessment. In this chapter, the underlying theory of this technique is reviewed. First the Fourier transform is presented followed by Fourier optics and the relationship between Fourier optics and surface texture. Finally, a description of the statistical parameters used in this investigation is presented.

3.1 Fourier transforms

In his investigations of heat flow problems J.B.J. Fourier [24] discovered that a periodic signal can be represented by an infinite sum of sine or cosine signals that are harmonically related. That is, a periodic function, \( f(x) \), can be represented by:

\[
f(x) = a_0 + \sum_{n=1}^{\infty} a_n \cos n\omega_0 x + b_n \sin n\omega_0 x \quad ......(3.1)
\]

Where \( n = 1, 2, 3... \)

\( \omega_0 = \) The fundamental frequency of \( f(x) \), i.e. \( \frac{2\pi}{\Lambda}, \Lambda \)

being the wavelength of \( f(x) \).

\( a_o, a_n, b_n = \) The Fourier coefficients.
Alternately, the Fourier series can be expressed in exponential form:

\[ f(x) = \sum_{n=-\infty}^{\infty} C_n \exp(jn\omega_o x) \] \hspace{1cm} ......(3.2)

Where \( j = \sqrt{-1} \).

And the \( C_n \)'s are the Fourier coefficients given by:

\[ C_n = \frac{1}{\Lambda} \int_{\Lambda} f(x) \exp(-jn\omega_o x) \, dx \] \hspace{1cm} ......(3.3)

Where \( \Lambda = \) The wavelength of the periodic function.

If \( g(x) \) is an aperiodic function then the Fourier transform of \( g(x) \) is represented by:

\[ G(u) = \mathcal{F}\{g(x)\} = \int_{-\infty}^{\infty} g(x) \exp(-jux) \, dx \] \hspace{1cm} ......(3.4)

Similarly the inverse Fourier transform is given by:

\[ g(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(u) \exp(jux) \, du \] \hspace{1cm} ......(3.5)

This means that, any function \( g(x) \) that is real, single-valued and encloses a finite area over the range of integration can be integrated as in equation (3.4) and hence Fourier transformed [24]. A function describing a
real surface profile will meet these requirements. If the profile is periodic the Fourier transformation will produce discrete Fourier coefficients ($C_n$'s) while if it is aperiodic the transformation produces a spectrum $G(u)$ in Fourier space. The Fourier transform process is equivalent to filtering a signal representing a profile with a narrow band pass filter. By using a large number of parallel narrow band pass filters, tuned to different frequencies, the RMS-value could be determined for these frequencies. The Fourier transform of a signal will then be obtained with an infinite number of narrow band filters whose width approaches zero. A graph showing the RMS-value of a signal as a function of frequency produces an RMS-spectrum. In vibration signal analysis, parallel digital filters are commonly used to obtain the Fourier spectrum. The optical Fourier transform provides equivalent results using an analog process.

3.2 Fourier optics

According to the electromagnetic wave theory [25], the electric field of a propagating light wave can be represented as:

$$E(t) = E_0 \sin \omega t$$

$$\ldots \ldots (3.6)$$

Where $E(t) =$ The time varying electric field signal.
\[ E_0 = \text{The maximum amplitude.} \]
\[ \omega = \text{The angular frequency.} \]

Diffraction patterns occur because of the interference of light waves. For example, if light is diffracted through a single slit (see Figure 3.1a), then a diffraction pattern (the Fraunhofer diffraction pattern) consisting of light and dark fringes is formed in the far field. This phenomena can be explained using Huygen's principle by assuming that each portion of the slit acts as a source of wavelets (see Figure 3.1b). Accordingly, the slit can be divided into a large number \((N)\) of equally spaced sources. To obtain the resultant amplitude of the light in the far field in a direction \(\theta\) (see Figure 3.1b), the contribution from \(N\) sources in that direction must be summed as follows:

\[
E_n = E_1 + E_2 + E_3 + \ldots + E_N
\]
\[
= \sum_{i=1}^{N} E_0 \sin[\omega t + (i-1)\phi]
\]

\[ \text{.....(3.7)} \]

Where \(E_n = \text{The resultant amplitude.}\)
\(E_i = \text{The contribution from the } i\text{'th source.}\)
\(i = 1, 2, 3, \ldots, N\)
\(\phi = \text{The phase difference between adjacent sources.}\)

As indicated in the diagram in Figure 3.1b, it can be shown that:
\[ \hat{\phi} = \frac{2n \alpha \sin \theta}{\lambda} \] \hspace{1cm} \ldots \ldots (3.8)

Where \( \hat{\phi} \) = The total phase difference between the 1st and \( N \)th sources (= \( N\phi \)).

\( \alpha \) = The width of the slit.

\( \theta \) = The angle between the normal and the direction of interest.

\( \lambda \) = The wavelength of the illuminating light.

From Figure 3.2 it can be shown that the amplitude, \( E(\theta) \), of the light forming the diffraction pattern is given by:

\[ E(\theta) = 2r \sin \frac{\hat{\phi}}{2} \] \hspace{1cm} \ldots \ldots (3.9)

And

\[ r = \frac{NE_0}{\hat{\phi}} = \frac{E_T}{\hat{\phi}} \] \hspace{1cm} \ldots \ldots (3.10)

Where \( E_T \) = The total source amplitude.

Therefore

\[ E(\theta) = E_T \frac{\sin \left( \frac{\hat{\phi}}{2} \right)}{\left( \frac{\hat{\phi}}{2} \right)} = E_T \sin \left( \frac{\hat{\phi}}{2} \right) \] \hspace{1cm} \ldots \ldots (3.11)

Since the intensity is proportional to the square of the amplitude, the intensity distribution is represented by:

\[ I(\theta) = I_T \left[ \frac{\sin \left( \frac{\hat{\phi}}{2} \right)}{\left( \frac{\hat{\phi}}{2} \right)} \right]^2 = I_T \left[ \sin \left( \frac{\hat{\phi}}{2} \right) \right]^2 \] \hspace{1cm} \ldots \ldots (3.12)
Where $I(\theta)$ = The intensity as a function of $\theta$.

$I_r = \text{The total source intensity.}$

This intensity distribution can also be derived through the use of the optical Fourier transform method [26]. To accomplish this, the slit can be represented by a single rectangle function as shown in Figure 3.3a. The Fourier transform of the slit function (Figure 3.3b) is obtained as:

$$T(u) = \frac{a}{\pi} \int_{-a/2}^{a/2} t_o \exp(-2\pi jux) dx$$

$$= t_o a \left[ \frac{\sin \pi ua}{\pi ua} \right] = t_o a \text{sinc}(\pi ua) \quad \ldots \ldots (3.13)$$

Where $T(u) = \text{The Fourier transform of the slit function.}$

$t_o = \text{The height of the slit function.}$

$a = \text{The width of the slit.}$

By comparing equations (3.11) and (3.13) it can be seen that they are equivalent: If $E_r$ and $\sin \theta / \lambda$ in equation (3.11) are replaced by $t_o a$ and $u$ respectively, then equation (3.13) is obtained. Therefore, the diffraction pattern formed in the far field can, in general, be expressed mathematically by the square of the Fourier transform of the object wave front in the plane of diffraction.
3.3 Fourier optics and rough surfaces

It has been shown that the scattering of light from surfaces whose surface height variations are much smaller than the wavelength of the light can be quantified using the diffraction model [10]. As when a single slit is used, the far field diffraction pattern produced by the rough surface will be related to the wavefront leaving the surface by a Fourier transform. The phase of this wavefront is modulated by the height variations of the surface. The modulated light waves will interfere in the far-field to form an interference pattern which is related to the surface height variations.

The path difference between two light rays, ray 1 and ray 2 (Figure 3.4), incident on a rough surface is given by:

\[ \Delta l_1 + \Delta l_2 = 2h(x)\cos\alpha \]  

\[ \ldots \ldots (3.14) \]

Therefore the phase modulation function, \( \gamma(x) \), can be expressed as:

\[ \gamma(x) = \frac{2\pi}{\lambda} [2h(x)\cos\alpha] \pm 2n\pi \]
\[ = \frac{4\pi h(x)}{\lambda} \cos\alpha \pm 2n\pi \]  

\[ \ldots \ldots (3.15) \]

Where \( h(x) \) = The surface profile.

\( \lambda \) = The wavelength of the illuminating light.
\[ \alpha = \text{The angle of incidence.} \]
\[ n = \text{A positive integer.} \]

For a unique representation of \( \gamma(x) \) [17], it is necessary that \( \gamma(x) \) be less than \( 2\pi \), or:

\[ (4\pi/\lambda)R_y \leq 2\pi \]

Where \( R_y \) = The maximum peak to valley surface height.

The reflected wavefront, \( p(x,t) \), just above the surface can now be represented by:

\[
p(x,t) = A_o \sin[\omega t + \gamma(x)] \\
= \text{Im} \left[ A_o \exp[j(\omega t + \gamma(x))] \right] \quad \ldots \ldots (3.16)
\]

Where \( A_o \) = The maximum amplitude.

The imaginary part of the exponential notation is equivalent of sine wave notation.

As the observed diffraction pattern is a time averaged representation of the light intensity, the time dependent part of the notation can be dropped without losing any important information. Moreover, if the amplitude is assumed to be unity then only the wave function dependent on the surface height variations is left, that is:
\[ p(x) = \text{Im}[\exp[j\gamma(x)]] \]  \hspace{1cm} \ldots \ldots (3.17) \\

The expansion of \( p(x) \) gives [17]:

\[ p(x) = \text{Im}[\exp[j\gamma(x)]] = \text{Im}\left[j\gamma(x) + \sum_{n=2}^{\infty} \frac{(j\gamma(x))^n}{n!}\right] \]  \hspace{1cm} \ldots \ldots (3.18) \\

Here the first term in the expansion, the number \( 1 \), has been dropped as only the imaginary part of the notation need be considered.

For \( h(x) \) much smaller than the wavelength of the light (\( h(x) \ll \lambda \)) the summation term in equation (3.18) can be neglected [17] and \( p(x) \) can be approximated by:

\[ p(x) \approx \text{Im}\left[j\gamma(x)\right] = \gamma(x) \]  \hspace{1cm} \ldots \ldots (3.19) \\

As demonstrated in section 3.2, the diffraction pattern in the far field can be represented by the Fourier transform of \( p(x) \):

\[ P(u) = \int_{-\infty}^{\infty} p(x) \exp[-jux] \, dx \]  \hspace{1cm} \ldots \ldots (3.20) \\

Therefore, if the surface height variations are much smaller than the illumination wavelength (i.e. \( h(x) \ll \lambda \)), then the diffraction pattern can be represented by the Fourier transform of the surface profile.
\[ P(u) = \int_{-\infty}^{\infty} \gamma(x) \exp[-jux] \, dx \]
\[ = \frac{4\pi}{\lambda} \cos \alpha \int_{-\infty}^{\infty} h(x) \exp[-jux] \, dx \quad \cdots (3.21) \]

The theoretical relationship between the surface roughness and the diffraction pattern formed in the far field by light scattering has been demonstrated. This derivation assumes that the roughness is much smaller than the wavelength of the illuminating light. Exact mathematical treatment of the integral in Equation (3.21) is possible for ideal profiles, including a Bessel function solution [17]. With this approach, it is possible to obtain a solution for surfaces with \( R_g \) values of up to about one tenth the illumination wavelength [17], but in general, the mathematics involved for interpretation of a real surface profile is quite laborious if not impossible.

3.4 Fourier transform pattern analysis

Most of the experimental work done on surface texture assessment by optical Fourier transform methods has been carried out on one dimensional surfaces, that is surfaces with only one lay direction. The resulting diffraction pattern from such a surface is a one dimensional spectrum. Figures 3.5 and 3.6. show two standard roughness samples having a regular saw-tooth profile as seen through a microscope. Their respective Fourier transform patterns are also shown. The resulting Fourier spectra for these
surfaces are shown in Figure 3.7. Parameters such as the height of the spectrum peak, its RMS height and the area of the spectrum have previously been correlated with roughness [20-22]. If a surface is two dimensional, however, then the diffraction pattern produced will be two dimensional (Figure 3.8) and it would be difficult to correlate the one dimensional parameters with roughness. In this work a method for evaluation of the two dimensional pattern is proposed to overcome this difficulty.

If the Fourier spectra of two surfaces (Figure 3.7) having different roughnesses are compared, it can be seen that the smoother surface produces a spectrum with higher and wider peaks that are more spaced out than those for the rougher surface. In order to quantify this change it is proposed that the grey-level intensity histograms for the patterns be calculated and statistical parameters from the histograms correlated with roughness. Grey-level histograms for the Fourier patterns in Figure 3.8 are shown in Figure 3.9.

For the purpose of defining the statistical parameters used in this investigation, the frequency distribution can be represented as an array of grey-levels, \( y \) ranging from 0 to 255. The respective frequency of occurrence of each grey-level in the Fourier pattern is denoted as \( f \). The statistical parameters can be defined as follows:
Mean grey-level:

\[ \mu = \frac{\sum_{i=0}^{\infty} f_i y_i}{\sum_{i=0}^{\infty} f_i} \]  \hspace{1cm} (3.22)

This is a measure of the central tendency of the histogram grey-levels.

Standard deviation:

\[ \text{SD} = \left[ \frac{\sum_{i=0}^{\infty} f_i (y_i - \mu)^2}{\sum_{i=0}^{\infty} f_i} \right]^{0.5} \]  \hspace{1cm} (3.23)

This is the square root of the second central moment and is a measure of the histogram spread about the mean.

Histogram skew:

\[ \alpha_3 = \frac{\sum_{i=0}^{\infty} f_i (y_i - \mu)^3}{\sum_{i=0}^{\infty} f_i} \]  \hspace{1cm} (3.24)

This is the 3rd central moment and measures the degree of asymmetry of the histogram.
Histogram kurtosis:

\[ \alpha_4 = \frac{\sum_{i=0}^{255} f_i (y_i - \mu)^4}{\sum_{i=0}^{255} f_i} \]  

......(3.25)

This is the 4th central moment and is a measure of the peakedness of the histogram distribution.

RMS histogram height:

\[ \text{RMS} = \left[ \frac{\sum_{i=0}^{255} f_i^2}{256} \right]^{0.5} \]  

......(3.26)

Where 256 is the total number of grey-levels available with this set-up.

This is a measure of the average height of the histogram.

Where \( i \) = The grey-level ranging from 0 to 255.

\( y \) = The light intensity in terms of grey-levels
(numerically equal to \( i \)).

\( f_i \) = The number of pixels at grey-level \( i \).

The relation between these statistical parameters and surface texture is investigated in this study. In the following chapter the experimental apparatus and procedure used is described.
Figure 3.1: a) Fraunhofer single slit diffraction pattern and intensity distribution [25].
b) Huygen's principle applied to diffraction of light through a single slit [25].
Figure 3.2: Phasor diagram for a large number of sources.
Figure 3.3:  
(a) Slit function.  
(b) The corresponding Fourier transform.
Figure 3.4: Path difference produced by surface roughness.
Figure 3.5:  
(a) Photograph of standard sample (Ra = 0.5μm).  
(b) The corresponding Fourier pattern.
Figure 3.6:  

(a) Photograph of standard sample ($Ra = 3.0\mu m$).  

(b) The corresponding Fourier pattern.
Fourier spectrum for standard sample
(Ra = 0.5μm)

Relative Intensity (grey level)

Spatial frequency (cycles/mm)

Figure 5.7a
Fourier spectrum for standard sample
(Ra = 3.0um)

Relative intensity (grey level)

Spatial frequency (cycles/mm)

Figure 8.7b
Figure 3.8:  a) Photograph of flat lapped surface (Ra = 0.2 μm).
               b) The corresponding Fourier pattern.
Grey level histogram
Standard sample, Ra = 0.5µm

Figure 5.9a
Grey level histogram
Standard sample, Ra = 3.0um

Figure 3.9b
CHAPTER IV
APPARATUS AND PROCEDURE

In order to derive the roughness information for the surface, the optical Fourier transform pattern is captured and analyzed by a microcomputer based machine vision system. In this section, a description of the apparatus is given, followed by the experimental procedure and analysis techniques.

4.1 Experimental apparatus

A schematic diagram of the experimental set up is shown in Figure 4.1. For details of equipment specifications see Appendix A. The apparatus is composed of an illumination system, an imaging system and an image processing system.

4.1.1 Illumination

The illumination system produces a spot of laser light on the sample. A 5mW He-Ne laser light source is used in conjunction with a 33µm spatial filter. Light emerging from the spatial filter is deflected by a beam splitter onto the surface of interest via an objective lens. The objective lens was chosen to produce a magnification of 10X. The effect of magnification is discussed in Chapter
v. The optical axis of this lens and beam splitter is perpendicular to the surface so that the illuminating light is incident at an angle of 90° to the plane of the surface. Light leaving the sample surface enters the imaging system.

4.1.2 Imaging

The imaging system is used to obtain a digital signal representing the Fourier pattern. The (phase modulated) light wave reflecting off the rough surface of the sample is reflected back through the objective lens, through the beam splitter and falls on a 45° mirror. The light reflected off this mirror passes through an imaging lens which is used to focus the Fourier pattern onto the image plane of a CCD camera.

The signal from the camera is fed into a digitizer and frame grabber. At this point the signal is digitized and captured. The gain and offset of the digitization board are adjusted as desired. The digitized signal is sent to a microcomputer for processing. Meanwhile, the digital signal is also displayed on a multisync monitor so that the captured Fourier pattern can be observed.

4.1.3 Image processing

A digital signal representing the optical Fourier transform pattern enters the image processing component of
the system. This image consists of 512 by 512 pixels each with a grey-level ranging from 0 to 255. The grey-level frequency histogram of the image is determined using a microcomputer image processing program. From this histogram, statistical parameters are calculated by the image processing program. These parameters can then be stored on disk for later analysis.

4.1.4 Auxiliary imaging system

In addition to the optical Fourier transform system, an auxiliary system is also set up for observation of the image of the surface. The illumination component of this auxiliary system consists of a white light source illuminating the surface at a shallow grazing angle. White light scattered off the surface enters the imaging component of the auxiliary system starting with the objective lens. For the auxiliary system the 45° mirror is removed and the image of the surface is focused onto the image plane of a second CCD camera directly above the surface. This is accomplished by varying the height of the camera.

The signal leaving the CCD camera is displayed on a high resolution monitor so as to facilitate the simultaneous observation of a magnified image of the surface with the laser spot in the field of view. This feature is used to position a flaw within the laser
projection area when desired and to estimate the size of the laser spot.

4.2 Experimental procedure

The procedure for determination of optical parameters used for texture evaluation is shown schematically in Figure 4.2. With the set-up shown in Figure 4.1 the Fourier pattern displayed on the multisync monitor was brought into focus by varying the relative height of the objective lens with respect to the roughness sample. Focusing is accomplished by obtaining the smallest, sharpest image. The Fourier pattern was then digitized, captured and stored with the frame grabber board. A picture of a typical captured Fourier pattern is shown in Figure 4.3.

The captured digital images consist of 512 x 512 pixels each with a grey-level between 0 and 255. From this array a grey-level histogram is obtained. As the image contains largely background information which is not relevant to this analysis, it is necessary to eliminate this background before computing the histogram. This was carried out by adjusting the offset of the frame-grabber board so that the grey-level of the background is digitized to zero, pixels with grey-level zero were subsequently ignored. For the present configuration, an offset of 70 (offset range 0 to 255) gives a zero
grey-level background.

Adjustment of the gain of the frame grabber board was also carried out to make use of the entire grey-level scale of the digitizer. In this set-up a gain of 120 (gain range 0 to 255) was used to give the brightest pixel of the image a grey-level value of 255.

From the histogram, several optical parameters were calculated. These are; the mean grey-level, the standard deviation, the skew, the kurtosis, the RMS height of the histogram. These parameters have been defined in Chapter III, equations (3.22) to (3.26).

Once the parameters were calculated, the results were stored in an ASCII file. This procedure was repeated with 4 different spots on each sample and the arithmetic mean is calculated to represent the reading for each surface. This procedure was repeated for all samples. In order to normalize the results, the 0.05μm (Ra) ground nickel sample was used. This reference sample was chosen as it produces very repeatable results when readings are taken at different locations on the surface. A set of 4 readings were taken on this sample before and after each experimental run or when there was a change in the set up to ensure the repeatability of the experiment.

The effect of surface flaws on the optical method was also investigated. To do this the auxiliary imaging system was used to observe the real image of the surface under white light. When the laser was turned on, its
illumination spot on the surface was observable on the image displayed on the high resolution monitor. A flaw was positioned in the field of view so that it was covered by the laser spot. Once the flaw had been properly positioned, optical parameters were calculated in a manner similar to the procedure described.

4.3 Roughness samples

Optical roughness parameters were obtained for samples of given materials. These parameters were normalized with the values obtained from the reference sample (Ra = 0.05 μm, ground nickel) to produce a dimensionless form. Plots of the histogram parameters (optical parameters) vs. roughness (Ra) were made to obtain the calibration curve for each class of samples.

Samples of stainless steel, brass, tool steel, nickel and magnesium were used in this study. The nickel samples consist of a set of surfaces manufactured by Rubert & Co. Ltd., England to have surfaces simulating different machining processes. The Rubert samples tested were the grinding and flat lapping samples. Other samples were made of different materials and were machined using different feed rates to produce various degrees of roughnesses.
Figure 4.1: Experimental set-up.
Figure 4.2: Experimental procedure flow chart for one class of samples.
Figure 4.3: Fourier pattern of a ground nickel sample (Ra = 0.2μm).
CHAPTER V
RESULTS AND DISCUSSION

In this study, a statistical analysis of the optical Fourier transform pattern was used to assess surface texture. Optical roughness parameters were determined for different materials produced by different machining processes (with various roughnesses) and correlated with the roughness as determined by the stylus. In addition, the application of these optical parameters for flaw detection was investigated. Here, the results of this research are presented and discussed.

5.1 Statistical parameters

In order to quantify surface roughness by the optical method, the grey level histogram of the optical Fourier transform pattern was found. From this histogram, statistical parameters such as mean, standard deviation, skew, kurtosis and RMS were calculated and correlated with surface roughness. The ground nickel samples were used as typical samples to show the correlation of the parameters with surface roughness.

5.1.1 Mean

Figure 5.1a shows a picture of the 0.2μm (Ra) ground
nickel sample as seen through the auxiliary imaging system. The optical Fourier transform pattern for this sample is shown in Figure 5.1b. This pattern is one dimensional with the peak intensity decreasing with increasing distance from the central bright spot. The histogram of this pattern (Figure 5.2) has an inverse power law form, i.e. frequency decreases as grey-level increases and then approaches zero at the end of the grey-level scale. Figure 5.3 is a plot of the mean grey level vs. Ra for nickel samples of various roughnesses. It can be seen from this plot that the mean grey level of the Fourier pattern tends to decrease with increasing roughness with the curve flattening out as roughness increases.

5.1.2 Standard deviation

From the histogram in Figure 5.2 the standard deviation of the grey-level was calculated. Figure 5.4 shows a plot of standard deviation vs. Ra for the nickel samples. This exhibits a trend similar to the mean grey level plot.

5.1.3 Skew

Figure 5.5 shows a plot of histogram skew vs. Ra for the nickel samples. In this case, the skew tends to increase with increasing roughness and the curve again
flattens out with increasing roughness.

3.1.4 Kurtosis

Figure 5.6 shows a plot of the histogram kurtosis vs. Ra for the nickel samples. This exhibits a trend similar to that of the skew plot.

5.1.5 RMS height

Figure 5.7 shows a plot of the RMS height of the histogram vs. Ra. Again this shows a similar trend to that of the skew plot.

5.2 Comparison of statistical parameters

In order to compare these different parameters, a normalization procedure was carried out as described in Section 4.2 producing dimensionless parameters. A plot of all normalized histogram parameters vs. Ra is shown in Figure 5.8 for the same nickel samples. As can be seen from this graph, the mean and standard deviation exhibit almost an identical change with roughness with the experimental set-up used. The skew, kurtosis and RMS all exhibit the same general trend, with the RMS showing the greatest sensitivity. For measurement purposes, the most desirable characteristic of the measurement is the
sensitivity. In order to obtain a parameter with maximum
sensitivity, the parameter \( R \) was defined as the standard
deviation divided by the RMS, ie:

\[
R = \frac{SD}{RMS}
\]

Where \( SD \) = The normalized standard deviation.

\( RMS \) = The normalized RMS.

This parameter, \( R \), was selected as the optical roughness
parameter and will be correlated with \( Ra \).

5.3 Important factors

It is necessary to investigate different factors which
may affect the \( R \) readings. Important factors that are
considered in this work include the size of the spatial
filter, the magnification of the Fourier pattern, and the
intensity of the laser light. The effect of these
parameters was investigated in order to determine their
importance and possible optimum settings.

5.3.1 Effect of spatial filter

To investigate the effect of the spatial filter on
measurements, two spatial filters were used, a 15\( \mu m \) and a
33\( \mu m \). Figure 5.9 shows the plot of Normalized \( R \) vs \( Ra \) for
both spatial filters. As can be seen from this plot, the calibration curves are very similar and the size of the spatial filter (between 15\mu m and 33\mu m) does not have a significant effect on the final results. A spatial filter of 33\mu m was used to take readings in this study.

5.3.2 Effect of magnification

Three different objective lenses were used to investigate the effect of magnification on measurements, these were 5X, 10X and 20X. Figure 5.10 shows pictures of Fourier patterns using 5X, 10X and 20X magnification.

Using these three lenses, the optical roughness parameter R was plotted against Ra and the resulting correlation curve is shown in Figure 5.11. The calibration curve for the 20X magnification exhibits much more scatter that the plots for the 5X and 10X magnifications. Meanwhile, the calibration curves for the 5X and 10X magnifications are quite similar and thus magnification does not appear to have a significant effect in this range. A magnification of 10X was arbitrarily selected for this investigation.

It is noted that, in addition to changing the size of the observed Fourier pattern, the magnification factor of the objective lens also affects the illumination spot size of the laser beam. To estimate this spot size, the auxiliary imaging system was used. In this process, the
spot size was compared to the size of an object of known dimension which was placed in the field of view of the imaging system. The results for spot size estimation are summarized in the table below:

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Approximate spot diameter (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5X</td>
<td>250</td>
</tr>
<tr>
<td>10X</td>
<td>130</td>
</tr>
<tr>
<td>20X</td>
<td>64</td>
</tr>
</tbody>
</table>

Table 5.1: Magnification and resulting spot diameter.

Changes in magnification therefore directly affect the laser spot size. The calibration curve shown in Figure 5.11 therefore reflects a change in both magnification and spot size.

5.3.3 Effect of light intensity

In order to investigate the effect of light intensity on measurements, a polarizer was used to vary the intensity of the laser light. Correlation curves were plotted for three different light intensities: (a) The maximum light intensity is achieved with no polarizer. (b) Light intensity is reduced when the polarizer is used with an orientation of 0° with respect to the illumination plane, i.e. the direction of polarization is the same as the
predominant polarization direction of the laser light. (c) The light intensity is further reduced when polarizer is oriented at an angle of 12° with respect to the illumination plane.

Figure 5.12 shows the correlation curves for normalized R vs Ra with various light intensities using the ground nickel samples. As it can be seen from this plot, the correlation curves are very similar for all intensities. It would appear that the curve for the lowest intensity (polarizer at 12°) may be shifted downwards as compared with the curve with the highest intensity (no polarizer). However, because of the normalization procedure, there is very little change in measurements due to changes in intensity. At higher intensities saturation may occur. This is manifested by a high peak at grey-level 255 in the histogram. All measurements in this study were taken with a light intensity slightly below the saturation level.

5.4 Characteristics of the Fourier spectrum patterns

Figures 5.13 to 5.18 show typical photographs of surfaces used in this study along with their corresponding Fourier patterns. The ground samples all have one lay direction and the Fourier patterns resulting form these samples are one-dimensional. With the flat lapping nickel sample, on the other hand, two lay directions are observed.
The Fourier pattern produced in this case is two dimensional but appears to be concentrated along two axes. With the oxidized magnesium sample, no lay direction is present and the surface is random. The resulting Fourier pattern is two dimensional and has no predominant axis.

5.5 Correlation between optical roughness, R and Ra

Figures 5.19 to 5.25 show plots of optical roughness, R vs. Ra for different materials and machining processes.

5.5.1 Grinding samples

Ground samples of brass, stainless steel, nickel and tool steel were used. The correlation curves for these ground samples were very similar. For a low Ra value, a high R value was obtained. For increasing Ra, this R value decreases and the curve tends to flatten out as roughness is greater than 0.6 µm Ra.

5.5.2 Flat lapping samples

For the nickel samples produced by flat lapping, it was found that normalization using the ground 0.05 µm (Ra) nickel sample produced very low R values as compared to ground surface of the same roughness. This could be because the flat lapping sample produces a two dimensional
Fourier pattern and normalization by parameters obtained from a one dimensional Fourier pattern is not valid. Therefore, normalization with the 0.05μm (Ra) flat lapping sample was tried and this produced a correlation curve consistent with the correlation curves for the ground samples. Hence, in the case of the flat lapping sample, this normalization procedure was used.

5.5.3 Random samples

The surfaces with random surface texture consisted of oxidized magnesium samples. For these samples, the R vs Ra plot does not produce any useful trend. This is probably because the magnesium samples were not very reflective and their reflectivity was not uniform due to the oxidized layer on the surface. This demonstrates that the optical method for surface roughness determination is dependent on the reflectivity of the surface under inspection.

5.6 Flaw detection

It was found that when a flaw was present on the surface, there was a significant reduction in the measured optical roughness (the R value). Figures 5.26 and 5.27 show this effect for ground stainless steel and brass samples when a defect was introduced. As can be seen from these plots, the difference in R values for the clean and
scratched surfaces is quite significant, especially for the smoother surfaces. Therefore, a reduction in \( R \) may be used to indicate the presence of a flaw using this method.
Figure 5.1: Ground nickel sample (Ra = 0.2\(\mu\)m).

a) Photograph of surface.
b) The corresponding Fourier pattern.
Grey level histogram
Ground nickel, Ra = 0.2um

Figure 5.2
Mean vs. Ra
Ground nickel samples

Figure 6.3
Standard deviation vs. Ra
Ground nickel samples

Figure 5.4
Skew vs. Ra
Ground nickel samples

Figure 6.6
Kurtosis vs. Ra
Ground nickel samples

Figure 5.6
RMS vs. Ra
Ground nickel samples

Roughness Ra (micrometer)

Figure 6.7
Histogram parameters vs. Ra
Ground nickel samples

Normalized histogram parameters

Roughness Ra (micrometer)

Figure 5.8
Optical roughness, $R \text{ vs } Ra$

Ground nickel samples

Normalized $R$ (SD/RMS)

$Ra$ (um)

+ spatial filter 15um  * spatial filter 88um

Figure 5.9. Effect of spatial filter.
Figure 5.10: Effect of magnification on Fourier patterns for ground nickel sample (Ra = 0.2μm).
(a) 5X magnification.
(b) 10X magnification.
(c) 20X magnification.
Optical roughness, R vs Ra
Ground nickel samples

Figure 5.11: Effect of magnification.
Optical roughness, R vs Ra
Ground nickel samples

Normalized R (SD/RMS)

+ polarizer 0 deg.  * polarizer 12 deg.
□ no polarizer

Figure 5.12: Effect of light intensity.
Figure 5.13: Typical ground nickel sample (Ra = 0.2μm). 
a) Photograph of surface. 
b) The corresponding Fourier pattern.
Figure 5.14: Typical ground brass sample (Ra = 0.3μm).
a) Photograph of surface.
b) The corresponding Fourier pattern.
Figure 5.15: Typical ground stainless steel sample (Ra = 0.2 μm).
   a) Photograph of surface.
   b) The corresponding Fourier pattern.
Figure 5.16: Typical ground tool steel sample (Ra = 0.4μm).
   a) Photograph of surface.
   b) The corresponding Fourier pattern.
Figure 5.17: Typical flat lapped nickel sample. 
(Ra = 0.1 \mu m).

a) Photograph of surface.
b) The corresponding Fourier pattern.
Figure 5.18: Typical oxidized magnesium sample. 
(Ra = 0.3μm).
- a) Photograph of surface.
- b) The corresponding Fourier pattern.
Optical roughness, R vs Ra
Ground nickel samples

Figure 5.19
Optical roughness, R vs Ra
Ground brass samples

Figure 5.20
Optical roughness, $R$ vs $Ra$
Ground stainless steel samples

Figure 5.21
Optical roughness, R vs Ra
Ground tool steel samples

Figure 5.22
Optical roughness, R vs Ra
Flat lapping nickel samples

Figure 5.29
Optical roughness, $R \text{ vs } Ra$

Oxidized magnesium samples

Normalized $R$ (8D/RMS)

Figure 5.24
Optical roughness, $R$ vs $Ra$
All samples

Normalized optical roughness

$Ra$ (um)

Figure 6.25
Optical roughness, $R$ vs $Ra$
Ground brass samples

Normalized $R$ (SD/RMS)

$Ra$ (um)

+ virgin surface  * scratched surface

Figure 5.26
Optical roughness, $R$ vs $Ra$
Ground stainless steel samples

Normalized $R$ (SD/RMS)

$Ra$ (um)

$\uparrow$ virgin surface  $\ast$ scratched surface

Figure 5.27
CHAPTER VI
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

An optical method for surface texture assessment of two dimensional surfaces was developed using an optical Fourier transform technique. This method utilizes a statistical analysis to derive parameters related to surface roughness. From this analysis, an optical parameter R was defined and related to Ra. The effect of spatial filter size, magnification and laser intensity on the method was investigated. Using the method, correlation curves for R versus Ra for different materials and machining processes were obtained. Finally, the effect of certain flaws on the method was determined. Following are the particular remarks from this work.

6.1.1 Statistical parameters

Surface texture of the machined surface was assessed using a grey level histogram. Five histogram parameters were investigated, namely: mean, standard deviation, skew, kurtosis and RMS, as defined in equations (3.22) to (3.26). For ground nickel samples, it was found that the curves of normalized mean and standard deviation vs. Ra both exhibited similar trends with the parameter decreasing with
increasing roughness. On the other hand, the normalized skew, kurtosis and RMS curves all increased in a similar fashion with increasing roughness. In terms of slope of the curves, the mean and standard deviation showed similar negative slopes while RMS exhibited the largest positive slope followed by kurtosis and skew respectively (see Figure 5.8). In order to maximize sensitivity, a parameter \( R \) was defined as \( \frac{\text{standard deviation}}{\text{RMS}} \). This parameter was then correlated with roughness.

6.1.2 Important factors

Considered in this work were some important factors that could potentially affect the \( R \) readings, namely: the size of the spatial filter, the magnification of the Fourier pattern, and the intensity of the laser light. It was found that, within the tested range, the size of the spatial filter, the magnification factor and the illumination intensity did not affect the \( R \) readings.

6.1.3 Correlation of \( R \) with \( Ra \)

Correlation curves for \( R \) vs. \( Ra \) for ground nickel, stainless steel, brass, tool steel, flat lapped nickel and oxidized magnesium were obtained. Except for the magnesium samples, all the samples produced similar correlation curves for \( R \) vs. \( Ra \). However, for practical use, each
different class of surfaces would require a unique correlation curve. The correlation curves could be used to assess surface texture for surfaces of unknown roughness.

This proposed method is applicable for surfaces with one lay direction as well as surfaces with two lay directions (i.e. one dimensional as well as two dimensional surfaces). The method did not produce useful results when the random surface, in this case magnesium, was tested. This is likely due the non-reflecting nature of the oxidized magnesium and the method should work with random surfaces that are more reflective. However, this demonstrates the dependence of the method on the reflectivity to the surface under inspection.

6.1.4 Flaw detection

It was found that the R value was significantly reduced when certain flaws were present on the surface. R could therefore be used to detect the presence of these flaws on the surface. This was demonstrated with brass and stainless steel samples. No effort, however, was made to quantify the severity of flaws.

6.2 Recommendations

a) The sensitivity of the method appears to increase with smoother surfaces. Therefore, the range of this technique
should be determined by experimenting with surfaces with roughnesses smaller than those studied here.

b) Light from a He-Ne laser light source (wavelength 0.6328μm) was used for this investigation. Dependence of the method on the wavelength of the light is unknown, hence, the effect of different wavelength of light should be investigated.

c) Further investigation is also necessary to confirm that this method is applicable for materials and machining methods other than those studied here.

d) The results for the magnesium samples indicate that the reflectivity of a surface affects the results. The effect of the reflectivity of a surface on roughness determination should be investigated.

e) An exact theoretical relationship between surface roughness and light scattering needs to be developed so that a mathematical approach and not an empirical approach can be taken with surface texture assessment by optical methods.
REFERENCES


APPENDIX A

EQUIPMENT SPECIFICATIONS
**He-Ne Laser**

Manufacturer: Opticon  
Model: LM2P, Class 'IIIb Laser product  
University of Windsor inventory control: 113045  
Wavelength: 0.6328μm  
Maximum power output: 5mW

**CCD camera (imaging system)**

Manufacturer: NEC  
Model: TI-23A  
Serial number: 234145  
Resolution: 542(H) x 492(V)  
Cell size: 11.8μm(H) x 9.8μm(V)

**Digitizer board**

Manufacturer: Matrox  
Model: PIP-1024  
Resolution: 512 x 512

**CCD camera (auxiliary imaging system)**

Manufacturer: Pulnix  
Model: RM-845  
Serial number: 001007  
Resolution: 800 x 490  
Cell size: 11.5μm(H) x 13.5μm(V)
Multi-sync monitor

Manufacturer: NEC
Model: JC-14013PU
Serial number: 69C08965U

High resolution monitor

Manufacturer: Panasonic
Model: WV-5410
Serial number: 97100409
1965  Born in Trinidad.

1982  Received Ordinary level Cambridge certificate at Campion College, Kingston, Jamaica.

1984  Received Advanced level Cambridge certificate at Campion College, Kingston, Jamaica.

1988  Received the degree of Bachelor of Applied Science in Engineering Physics from Queen's University, Kingston, Ontario.

1991  Currently a candidate for the degree of Master of Applied Science in Mechanical Engineering at the University of Windsor, Windsor, Ontario.