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The Use of a Complete Surface Profile Description to Investigate the Cause and Effect of Surface Features

R.F. O'Connor,
School of Manufacturing
and Mechanical Engineering,
The University of Birmingham,
Birmingham, United Kingdom.

T.A. Spedding,
School of Mechanical and Production Engineering,
Nanyang Technological University
(to be established in July 1991),
Singapore 2263.

Abstract

Until recently, the assessment of a complete surface profile, in terms of both roughness and waviness characteristics, has been restricted by both instrumental and computational limitations. This has meant that previous descriptions of surface texture could not fully recognize the functional aspects of surface interactions. Similarly they were limited in identifying the machining conditions necessary to obtain the optimum surface characteristics for a specific functional application.

This paper reviews a complete and unified surface profile characterization scheme developed by the authors. The approach identifies the random and periodic elements of the surface profile naturally, as opposed to the traditional techniques which attempt to relate roughness and waviness to assignable causes at an early stage of assessment. This leads to a more flexible and comprehensive characterization.

To improve the understanding of the functional evolution of a surface, a study is presented which aims to establish the surface conditions necessary to obtain a desired functional performance. These characteristics are then related to manufacture so that the ideal machining characteristics can be established.

It is therefore shown that a greater understanding of the machined surface can be obtained in terms of causes and effects, in a way that links manufacture to function via the characterization scheme.

1.0 Introduction

The increasing demands made on component design mean that surface specification for a desired performance can no longer be treated in isolation from the details relating to manufacture and functional requirements of the surface.

Until recently, the assessment of a complete surface profile, in terms of both roughness and waviness characteristics, has been restricted by both instrumental and computational limitations. This has meant that previous descriptions of surface texture could not fully recognize the functional aspects of surface interactions. Similarly they were limited in identifying the machining conditions necessary to obtain the optimum surface characteristics for a specific functional application.

This paper presents details on a complete characterization scheme that provides a significant contribution towards "closing the loop" between manufacture and performance. It yields a unified mathematical treatment of both roughness and waviness characteristics, without recourse to functional considerations, and provides a more scientific and natural approach to surface finish analysis.

The roughness of a surface will have a secondary effect in most functional situations where significant waviness is detected. To illustrate the potential of using a complete characterization to study the causes and effects of surface features, the examples presented here concentrate on surface profiles which exhibit significant waviness, so that the effect of such features may be fully appreciated. Many similar studies have been conducted for roughness but waviness is usually ignored.

The techniques presented offer a complete characterization which identifies the respective contributions of roughness and waviness to the surface. The functional significance of waviness is shown to be of primary importance where it makes a significant contribution to the amplitude of the surface.

2.0 The Characterization Scheme

Conventional treatment of surface texture characterization is usually based on analyzing surface roughness, where waviness is previously removed by mechanical, electrical or digital filtering. A unified model which attempts to address the problem of functional performance must take into account both roughness and waviness characterization.

The characterization scheme adopted here distinguishes between the random and periodic elements of the surface, deeming them as roughness and waviness respectively. The characterization scheme then allows the surface components to be analyzed as a complete model or individually so that the effects of roughness and waviness can be assessed in isolation from another.
The features of the machined surface can be naturally separated into these components by considering the nature of the conditions under which they evolve. The asperities which result from the tearing of material during machining are generally of random nature, and are normally deemed roughness. Other surface features are produced as an artefact of the machining process. That is, waviness is generally the result of cyclic instability within the cutting system [1], whilst a single point cutting process will have a tendency to introduce feedmarks onto the machined surface. These features can be regarded as primarily periodic.

Therefore if a profile is separated into two series of random and periodic features, these series can be modelled separately, then recombined to produce a 'complete' and unified characterization of the profile. This is the approach adopted for the characterization scheme proposed in this paper. It is shown that the resulting model is statistically equivalent to the measured profile, and can be used to study the cause and effect of surface features.

To characterize the profile directly use is made of Wold's decomposition theorem [2] which states that a discrete stationary process can be expressed as a sum of two uncorrelated processes, one deterministic the other indeterministic.

The separation of random and periodic components must be achieved so as to leave both data-types intact. Several approaches to the characterization of roughness have been suggested. These however involve the removal of any waviness which may be present on the surface by electronic &/or digital filtering methods thus losing the information content of the periodic &/or long wavelength component.

To this end, a rigorous method was developed [3] to characterize periodicity, and in particular surface waviness. The technique identifies and directly models the main profile harmonics using a simple set of sinusoids. A mathematical model which is a close approximation to the original waviness is obtained. The model can be separated from the original profile by subtraction in the time domain. It has been shown [4] that this technique does not significantly affect the spectral estimate of frequencies, other than the band it removes. In this way, the surface data does not suffer from distortion, and there is no loss of profile information.

3.0 The Characterization of Waviness

Figure 1 shows a flowchart of the overall characterization procedure, and consists of three main steps;

(i) Fourier (harmonic) analysis of the original profile to obtain initial frequency estimates of the main waviness components. These estimates are identified to an accuracy better than $2\pi/n$ of their true value so as to avoid the effects of sidelobing when applying the harmonic regression algorithm.

(ii) Harmonic regression uses these initial estimates to compute accurate estimates of frequency, amplitude and phase, of the 'best-fit' sinusoids.

(iii) This information is used to generate a sinusoidal model which will represent the main waviness trend of the profile.

The three stages are outlined in greater detail below:

3.1 Fourier (harmonic) Analysis

The periodicities within a measured profile are identified using a Fast Fourier Transform technique. The profile is decomposed into a sum of sinusoidal components, with frequencies that are harmonics of the fundamental frequency. The fundamental frequency is the lowest frequency which can be fitted to the data, and corresponds to one cycle within the entire profile length.

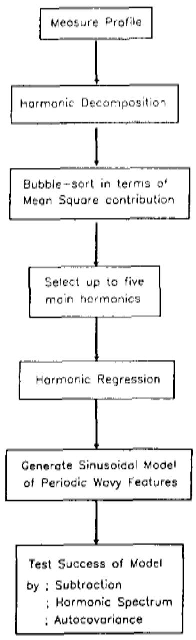


Figure 1 Flow Chart of the Characterization Process

For many machining processes, surfaces are produced which possess directional feedmarks. Generally the feedmarks are periodic in nature, and would represent a dominant frequency component with regard to harmonic analysis. To facilitate the analysis procedure, the harmonic(s) corresponding to the feedrate used during machining are identified.

To ascertain how many, and which harmonics to include in a particular model, a bubble-sort algorithm was used to sort the harmonics in terms of their mean square contribution. The cumulative contribution was expressed as a percentage of the

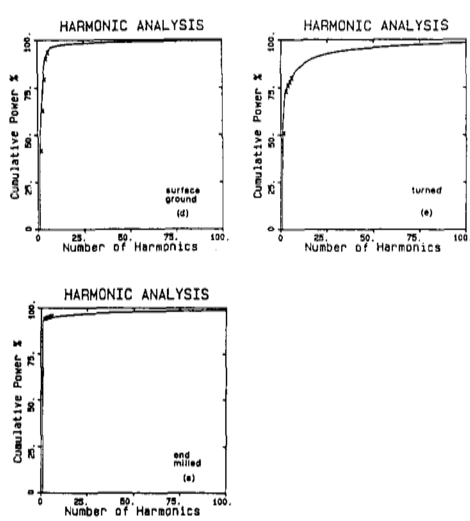


Figure 2 Graphs of Cumulative Percentage Contribution versus 'Bubble-sorted Profile Harmonics

total mean square error, and plotted against the number of harmonics. In this way, the percentage contribution for a number of dominant harmonics could be assessed. A range of wavy &/or periodic surfaces were assessed in this manner. Some examples of the resulting plots are shown in figures 2(a)-(c).

The results indicate that when modelling surface waviness &/or periodicity, it is prudent to use up to five of the most dominant low frequency harmonics to generate a sinusoidal model. Moreover, these main harmonics typically constitute over seventy five percent of the total profile variance.

3.2 Harmonic Regression

Accurate estimates of frequency, amplitude and phase, for the main harmonics identified using the Fourier analysis above, are obtained by harmonic regression. The technique establishes the least squares 'best-fit' sinusoids to the main waviness components of a surface profile. Cyclic descent is used to optimize the value of each parameter.

3.3 Generating the Model

A sinusoidal modelling technique then uses the accurate estimates of frequency, amplitude and phase to generate a model of the surface waviness. The surface waviness is therefore represented by a model of the form

$$R_1 \cos(\omega_1 x + \Phi_1) + \dots + R_n \cos(\omega_n x + \Phi_n) \qquad \dots\dots (1)$$

where for each harmonic, R is the amplitude, ω represents the frequency and Φ is the phase.

3.4 Remarks

The modelling technique has two uses;

(i) It may be used to model the waviness features only, so that the cause of these features can be investigated.

(ii) For surfaces which are ordinarily periodic in nature, the 'complete' periodic structure can be modelled. This model can be separated from the random roughness, which can then be modelled using time series techniques outlined in section 4.0.

The characterization process can be used to model the waviness (or lobing) of component roundness. This entails 'straightening' the roundness data and then characterizing as for a linear surface trace. On completion the model can be plotted as both a 'straightened' and a roundness trace. In this way, the waviness which constituted the component out-of-roundness is treated and assessed in a similar fashion to linear waviness.

4.0 The Characterization of Roughness

It has long been realized that the characterization of the random structure produced by surface roughness must take into account both its height and spatial properties. Time Series Modelling techniques and in particular Autoregressive Moving Average Processes developed by Box and Jenkins [5], and suggested for surface metrology by Stralkowski [6], offer a powerful technique of combining height and spatial properties of a surface profile into a single model. The biggest limitation of these models is that they can only be used to model surface profiles with a Gaussian height distribution.
To develop a generalized approach to roughness characterization these models were extended to non-Gaussian processes [7 & 8] so that surface roughness with non-Gaussian height distributions could also be accurately modelled.
Once the waviness component of the surface has been identified and removed by the techniques outlined in section 3.0, the remaining random component which represents the surface roughness can be modelled directly using a non-Gaussian autoregressive process. A single model is obtained which consists of a complete description of the roughness of the surface profile in terms of its height and spatial properties.

A further advantage of these techniques is that they offer a powerful simulation tool in which profiles which are statistically equivalent to the original surface roughness can be generated. The properties and structure of the surface for specific functional requirements can then be studied.

5.0 A Complete Characterization

By combining the characterization techniques outlined in sections 3 and 4 a complete surface profile characterization of both waviness and roughness may be generated. An example of a complete profile characterization is illustrated in figures 3(a)-(e). The original profile, taken from a plunge ground surface, is shown in figure 3(a), together with its height distribution and autocorrelation function. The profile consists of random roughness superimposed on an under-lying surface waviness, and possesses a Gaussian height distribution.

The waviness of the original profile was modelled using the four most dominant harmonics and is shown in figure 3(b). The remaining roughness profile (figure 3(c)), produced by subtraction of the waviness model, was simulated using a non-Gaussian Autoregressive Process of order 3, and is shown in figure 3(d). Although in this instance the profile is Gaussian, the technique is a generalized time series method, that can also model non-Gaussian random components with equal success.

Figure 3(e) shows the complete simulated profile as produced by recombining the two separate models. Comparison of the height distribution and autocorrelation function of the original and simulated profiles, reveals that the model is statistically equivalent to the original surface profile. The original profile is therefore closely approximated by a mathematical model of the form,

$$\begin{aligned} y_x = {} & 1.184y_{x-1} - 0.403y_{x-2} + 0.186y_{x-3} + a_x \\ & + 1.216\cos(0.0046y_x + 1.053) \\ & + 0.769\cos(0.0072y_x + 0.765) \\ & + 1.310\cos(0.0105y_x - 1.543) \\ & + 0.940\cos(0.0144y_x + 0.781) + 5.085 \end{aligned}$$

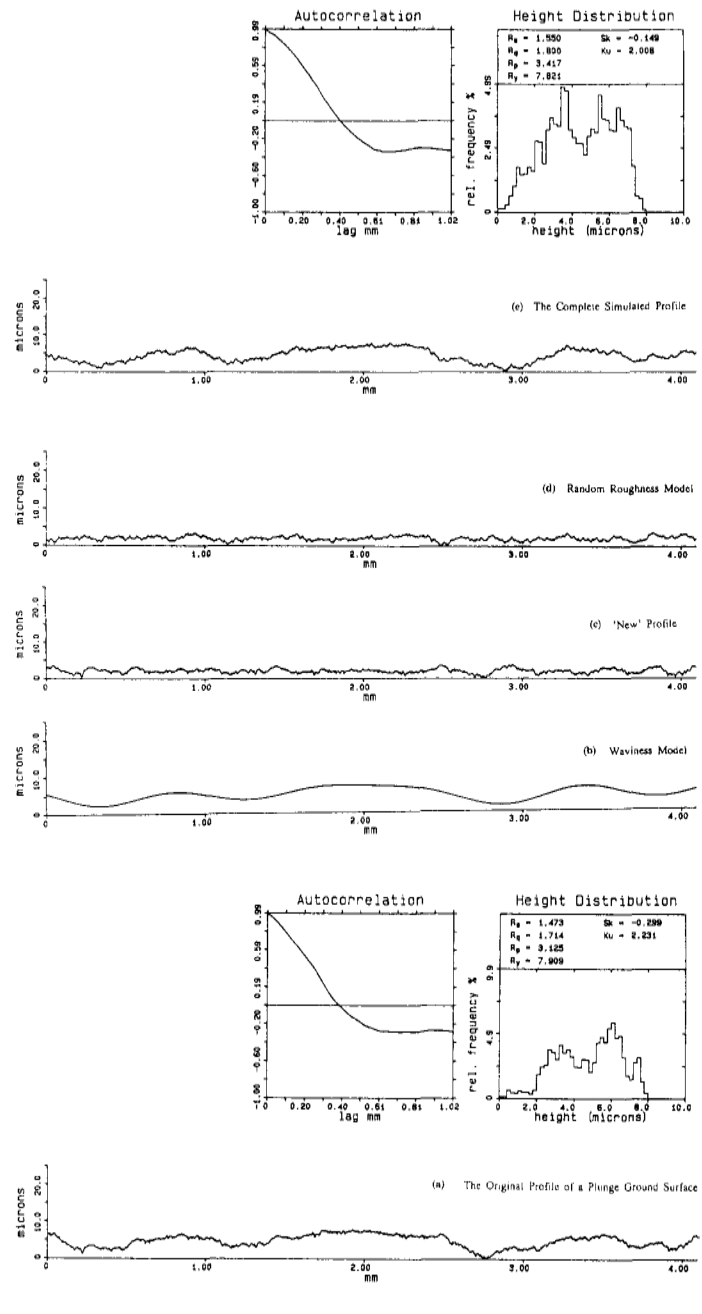


Figure 3 A Complete Profile Characterization

where a_x is a white noise term with; mean = 0
standard deviation = 0.157
skewness = 0.003
kurtosis = 3.168

6.0 Using the Characterization Scheme to Investigate Causes

Aspects of the characterization scheme can be used to study the cause(s) of specific surface features. A technique was developed that enabled the vibratory conditions experienced close to the cutting region during machining to be recorded [3]. Vibration data relating to specific cutting conditions can then be analyzed with respect to resulting surface features, and in particular waviness. The method identifies and models the dominant vibrational frequencies in a similar manner to the characterization of waviness. It is therefore possible to assess the relationship between the recorded vibrations and surface waviness, and it also provides the basis for identifying those process variables that must be controlled to minimise waviness.

The technique utilizes a vibration transducer that is positioned either on the tool or on a 'key' part of the machine structure close to the cutting region. Therefore any vibrations that are likely to modulate the machined surface can be measured.

Fig. 4

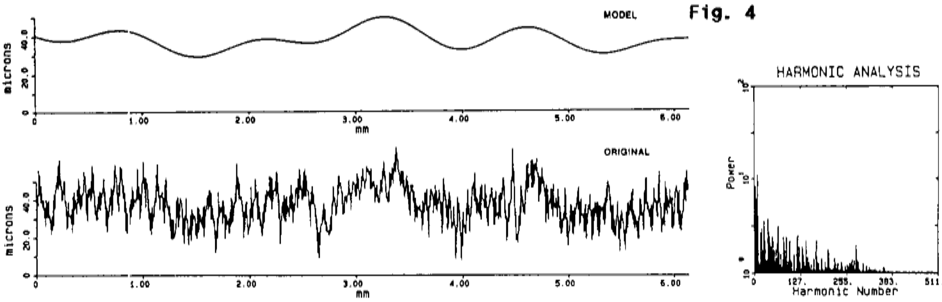
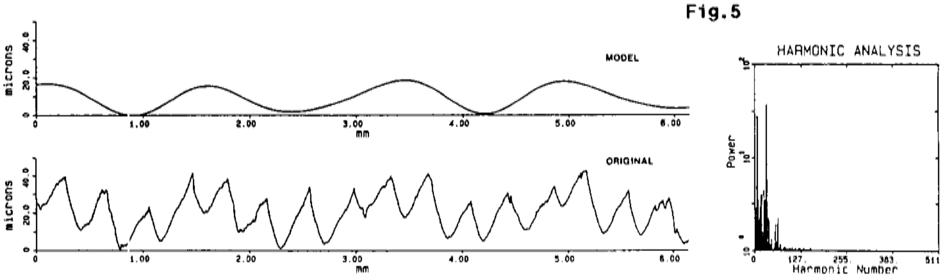


Fig.5



Figures 4 & 5 Original and Modelled Profiles for the Vibration and Surface Records Respectively

To-date the technique has been applied to vibration analysis of the turning and surface grinding processes.

An example is now presented to qualify the methodology of the assessment procedure as applied to the turning process.

(a) Translate the vibration record from a frequency base to an equivalent spatial distance

Figures 4 and 5 show the original waveforms for the vibration and surface records. The vibration data is translated to have a sampling interval based on spatial distance rather than frequency or time.

(b) Identify the dominant harmonic components prevalent within the vibration and surface records

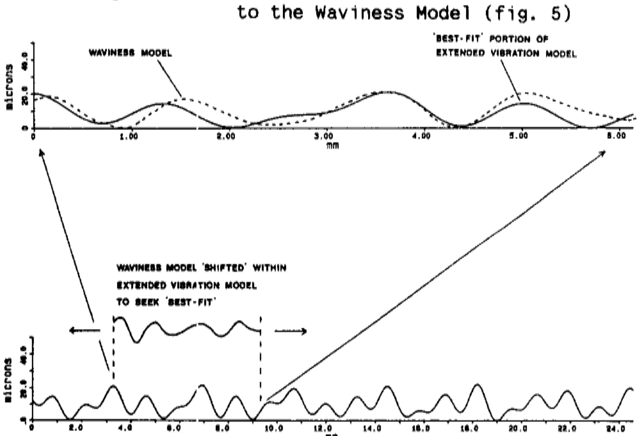
(c) Harmonic line spectra are constructed for each waveform, and are plotted on the respective figures 4 and 5. Visual comparison of the spectra provides an initial indication as to the similarity between predominant, individual harmonics and also the overall trend of the spectrum.

(d) Use harmonic regression to compute accurate estimates of frequency, amplitude and phase for the dominant low frequency harmonics as identified by the harmonic analysis.

(e) Sinusoidal models for both waveforms are generated using this information.

In this instance, a similar harmonic structure relating to the low frequency vibrations and waviness features exists. It is apparent however that a phase difference exists between the two models. This is due to the nature of the data collection. It is difficult to effect an accurate relocation technique, to trace the machined surface at exactly the place of logging the vibration data.

Figure 6(b) 'Best' Fit Vibration Model Relative to the Waviness Model (fig. 5)



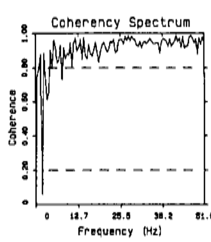


Figure 6(c)

Coherency Spectrum

Figure 6(a)

Extended Vibration Model Generated from the Model in Figure 4

(f) Generate an extended vibration model

If a repetitive low frequency trend exists within the vibration data, then it is prudent to assume that this will continue to prevail throughout the cut (providing nothing upsets cutting conditions). The low frequency trend is mathematically defined and is a continuous sinusoidal function. Therefore, using the function an extended model can be generated which would represent the low frequency oscillations experienced by the tool throughout the cut. Figure 6(a) shows the 'extended' vibration model as generated from the short-model function.

(g) Identify the position which minimizes the residuals when subtracting the surface trace from that portion of the extended model

A process was developed to identify the portion of the extended vibration model which represents minimum phase difference between the two models: The waviness model is shifted within the extended model until finding the position at which the residual error between the two models is a minimum.
The corresponding portion of the extended vibration model is then extracted and saved as a 'new' model of equal file length to the surface trace. Figure 6 (b) shows the 'new' vibration model plotted over the waviness model shown by the dashed trace. Visually it can be seen that the phase difference between the 'new' model and the surface waviness model has been reduced.

(h) Test the coherency between the two data records

The coherency spectrum of the vibration model versus the original surface structure is shown in figure 6(c). Coherency at the low frequency region reveals that a relationship exists between the low frequency vibrations and the surface waviness. Correlation at the higher frequencies is due to the absence of high order harmonics for both data records.

For this example it can be concluded that both models are closely correlated. The models are derived from the dominant harmonics, which are of low frequency, prevalent within the respective waveforms. Therefore, the dominant tool oscillations are of a low frequency nature, and these are directly related to the waviness introduced onto the machined surface.

This analysis procedure was used to help assess the relationship between tool/machine vibrations and waviness as part of an extensive test programme for the turning and surface grinding processes.

For surface grinding it was observed that machining instability resulted in very dominant cyclic vibrations, and was largely due to grinding wheel imbalance. There was a definite relationship between waviness amplitude and the magnitude of wheel imbalance, and waviness wavelength and machine table feedrate.

The schedule of turning tests consisted 144 tests, and was derived so that the range and combination of variable settings yielded a broad spectrum of cutting conditions. The turning process involves more process variables that influence cutting stability. Even so, the analysis procedure identified up to a 74% correlation between dominant low frequency vibrations and surface waviness.
A classical factorial design approach was used to design the turning experiments. It was then possible using ANOVA (Analysis Of Variance) to identify the significant main effects and/or interactions of process variables with respect to the response variable waviness. Table 1 shows the results in terms of what factors have an individual &/or a combined effect on surface waviness and component out-of-roundness.

Main Effects And Interactions For The Turning Tests

Response Variable	Main Effects					Interactions				
	Tool Overhang	Depth of Cut	Spindle Speed	Feedrate	MRR	O/H Speed	O/H DOC	DOC Speed	O/H DOC Speed	O/H Feed Speed
Wq	✓	✓	△			✓				
Wy	✓	✓	△			✓				
lWq				✓		✓				✓
P-V	✓	✓				✓		△		
No. Lobes			✓			✓				

Table 1

✓ Primary Effect

△ Secondary Effect

A study of this nature, generates information which effectively 'characterizes' a machining process, with regard to cutting stability. This knowledge can be used to control the process to maintain quality, and also for diagnostic purposes.

7.0 Using the Characterization Scheme to Investigate Effects

The characterization scheme produces separate and combined mathematical representations of roughness and waviness that can be used for simulation. This enables the contact level between surfaces for both static and dynamic situations, to be estimated.

For example, it is possible to generate real or synthetic wavy models, and the extent of contact at a specified level of interaction then assessed. To simulate the relative motion between surfaces, one model can be 'shifted' relative to an extended-length model. This process is similar to that used when seeking minimum residuals between a vibration and a waviness model.

Figure 7(a) shows two wavy ground surfaces in contact for a static contact situation. The waviness of each surface was modelled, and the resulting models are shown in figure 7(b). The lower model represents an extended model consisting of 4096 points at 4 um sample spacing, as generated from the waviness of the lower profile in figure 7(a). The upper model consists of 2048 points, has the same sample spacing, and has been inverted such that its wave crests contact the mating profile. In this instance, the models are assumed to interact at the 90% tp level, which represents a 10% elastic yield at the crests of the contacting waves for both surfaces. At the specified level of interaction, both the extent of contact and the unit void volume can be assessed. By systematically shifting the upper model relative to the longer model, the change in the mode of contact can be examined.

Figure 8 shows how the level of contact changes when the upper model is shifted relatively to the extended waviness model. Therefore the technique makes it possible to establish a more realistic estimate of the maximum level of contact, than that obtained from a 'static' estimate. This approach is only possible because the characterization scheme provides a mathematical

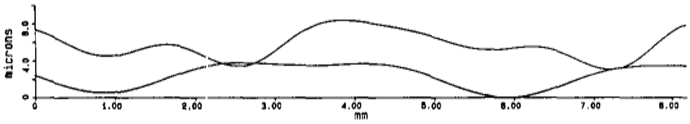


Figure 7(b)

Waviness Models, Genearated from the Profiles in Fig. 7(a), at a 90% Interaction Level

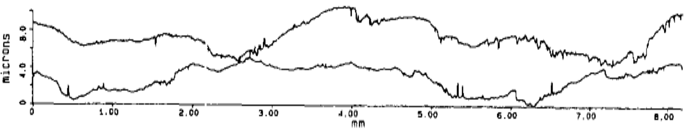


Figure 7(a) Two Wavy Ground Surfaces in Static Contact

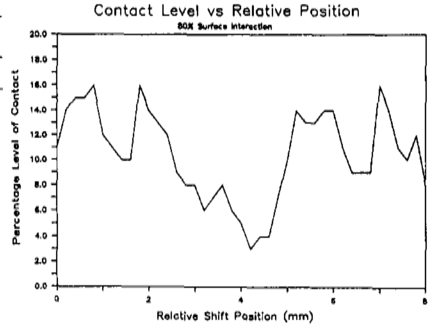


Figure 8

The Changing Level of Contact for the Two Surfaces (Fig. 7(a)) for a Dynamic Contact Situation

description of the surface waviness, which makes a dynamic mathematical simulation possible.

Although only in the early stages of development, this approach enables the effects of differing forms of waviness to be predicted analytically. Obviously, the level of interaction will depend on the applied load, the mechanical characteristics and interaction of the surfaces. Nevertheless, by adopting a level such as the 90% tp level, a first approximation as tc the contact and tolerable scale of waviness can be ascertained.

8.0 Discussion

The general engineering practice of specifying surface finish, is usually in terms of the scale of roughness in conjunction with a designated process. It has long been appreciated that this does not adequately describe surface topography. Furthermore, with the increasing demands of process control and product performance, a complete characterization of engineering surfaces in terms of the height and spatial characteristics is necessary.

The traditional approach of filtering on a spatial basis is subjective, and does not account for the fact that a surface can possess a continuous spectrum of wavelengths. This approach has the effect of relegating waviness to a secondary effect, without any scientific justification. Waviness is functionally important; generally it will be detrimental to surface performance since it will affect both the tribological and metallurgical aspects of the surface [9,10, &11]. Also waviness generally represents a deterioration in the machining process [12]. For these reasons it is important that it is measured and assessed for the purposes of process control and functional performance.

The accepted methods of treating waviness have been based on filtering techniques that have developed from electrical filters to the digital equivalents used on modern computerized systems.

The main problem with these methods is that although they usually adequately represent the waviness of a surface they do not provide a mathematical description. This precludes any form of scientific analysis into the behaviour and effects of waviness in terms of both the machining characteristics and functional assessment.

With the advances in computational methods it is now possible to directly model the surface profile. This can be achieved by separating the random and periodic features of the profile and modelling each series individually. The two models can then be recombined to give a complete characterization.

9.0 Conclusions

A complete and unified characterization scheme was developed and has been used successfully to model a wide range of engineering surfaces. The technique uses Fourier analysis and harmonic regression to generate a sinusoidal model of surface periodicity. This model is then subtracted from the original profile, in the time domain, thereby leaving both data types intact. The remaining random roughness is then modelled using non-Gaussian autoregressive time series techniques.

The scheme has the advantage of providing a complete mathematical description of the surface in terms of height and spatial characteristics. The model reflects the nature and evolution of the surface features in a way that is statistically equivalent to the original surface profile. In this way, a simulation model is established so that the properties of the surface in terms of causes and effects, can be investigated by a scientific and mathematical analysis.

The method for characterizing waviness was used as a basis of a practical study to investigate the evolution of waviness on the machined surface for two common surface preparation techniques. Effectively the process could be characterized in terms of the conditions that generated waviness. It was therefore possible to establish the relationship between tool (or machine) vibrations and surface waviness features. In this way, the optimal process conditions to provide the desired surface characteristics, can be identified and controlled.

The modelling technique can also be applied to simulate the effects of actual waviness or synthetically generated waviness, in a contact situation. The mathematical model can be applied to establish the maximum level of contact and void volume, for a wavy surface in a static or dynamic situation. The method provides a first approximation to the 'acceptable' levels of waviness for a particular function.

Moreover, the waviness model is comparable to the waviness representations produced by recognized filtering methods, but has the added advantage of yielding a mathematical characterization.

The model is separated from the original profile by simple subtraction in the time domain. The surface data is therefore left intact, and there is no loss of surface information.

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