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Surface Finish, Friction and Wear; The Need for More Than One Parameter

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Institute for Basic Standards
National Bureau of Standards
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Final Report

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
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Introduction

Friction and wear are familiarly known to be complex phenomena dependent upon the mechanical and chemical properties of the surfaces in contact and the lubricant used to separate them. In order to manufacture equipment with predictable lifetimes and performance characteristics under loads, it has become necessary to evaluate a multitude of these material properties. The topography, or surface finish, of parts has been seen to strongly influence among other things, frictional forces, the load carrying capacity of gears, the dynamics of lubricational properties, and the wear lifetimes of bonded solid lubricants. However, it has become clear that single parameter characterization of surface finish (e.g. by means of AA or RMS roughness values) is an inadequate means of describing surface finish and its functional relation to friction and wear.

The purpose of this report is to consider in a very elementary way the cause of this inadequacy and to briefly consider some of the presently implementable alternatives.

Specification of Roughness

At present, the most common specification of surface finish is by means of an AA roughness value, usually coupled with a description of the process by which the surface is finally formed, e.g., by milling, grinding, etc. The AA roughness is derived from a two-dimensional profile of the surface generated by a stylus instrument. Recent literature in surface finish demonstrates a growing awareness of the great difficulty of succintly characterizing a given profile once a valid one is obtained. While AA values can be obtained with a reasonable degree of accuracy and repeatability, they cannot be correlated very well with product function and reliability, (although an inverse relation with cost has been revealed). Thus, when an engineer calls for a finer finish, he may not be sure of the effect on lubrication properties or load carrying capacity of a gear.

Since the limitations of using only one parameter (AA) are known, other means of characterizing surfaces via profiles have been attempted. Bearing area curves, maximum peak heights, average peak-to-valley distances, or peak height densities have been specified and commercial instruments are available for their measurements. Some indication will not be given as to why these parameters are prone to the same type of difficulties as AA values, namely insensitivity to and inability to distinguish different types of surface structure. In a later section some more useful "second parameters" will be discussed.

The limitations of a Single Parameter

In Figure 1 are shown seven profiles, more or less physically realizable and associated with different formation processes. The first two are complex, with some repetitive structure, and are reminiscent of profiles of milled or ground surfaces. The next two are almost purely sinusoidal, differing, however, in wavelength. Although machining of such surfaces would be difficult, there are on the market surface roughness standards produced by photo-etching of light interference patterns that have such profiles. The fifth profile corresponds to the triangular waveform of another type of surface roughness standard. The last two profiles are highly idealized and correspond to surfaces having repetitive grooves and ridges, respectively. The significance of these profiles lies in the fact that, although they vary widely in character, they could all have the same AA roughness value. To see why this is possible consider the following exercise which involves only a minimum amount of sleight-of-hand.

A Game with Numbers

Figure 2 shows a collection of fifty digits, consisting of five each of the numbers one through ten. Some standard mathematical quantities are associated with this collection, some of which are indicated in Figure 3. The average (or mean) value is the sum of all the digits, divided by the number of digits; the average deviation from the mean is the sum of the absolute values of the differences between each digit and the mean, divided by the number of digits; finally, the standard, or root mean square deviation from the mean, which is the square root of the sum of the squares of the differences of each number from the mean, usually divided by one less than the total number of values. The range of the numbers is the difference between the highest and lowest.

There may also be associated with the collection some type of distribution curve. Figure 4 shows the number of times each digit appears and the graph shows the fraction of the total number of digits which have values less than a given digit.

Now consider what a profile instrument does when it measures some characteristic of a profile. It effectively associates some number, an ordinate, with the vertical displacement of the stylus and then performs by analog circuitry some mathematical operation. Figure 5 shows the relation between the mathematician's and the surface metrologists's names for a given parameter. The average corresponds to the centerline; the average deviation to the AA (or CLA) roughness; the standard deviation to the RMS roughness, the range to the maximum peak-to-valley distance over an interval, and the distribution to the bearing area curve. Figure 6 shows diagramatically what these parameters correspond to on a profile.

The Sleight of Hand

By taking our original collection of fifty numbers and representing each number as a line on a bar graph, one can construct any number of profiles (about 10^{64} for fifty numbers). Five are shown in Figure 7. The first is merely to indicate the constituent numbers. The next four are, however, realizable surface profiles with striking and significantly different characters. It should be remembered that all these profiles are made up of the same fifty ordinates and, therefore, have identical center lines, AA, RMS and maximum peak-to-valley parameters as well as identical bearing area curves. The point to be made is that these parameters are measures of ordinate height only and are by nature insensitive to the ordering or sequential alignment of the heights involved. Further, this insensitivity is not due to instrument design or implementation. (As an aside, the variations shown in the Figure could very well fall within the band pass characteristics of an averaging meter, AA or RMS, and not be greatly effected by the cut-off setting).

There are, however, mathematical tools for analyzing profiles which taken into account the ordering of the profile ordinates. Instruments for this type of analysis are commercially available; some involve software programmed computer analysis, others have hardware which perform similar functions. Such instrumentation tends to be quite expensive and the original analysis time-consuming and sophisticated. With these disclaimers in mind, let us, just for fun, consider what auto-correlation and frequency spectrum analysis can tell about surface roughness.

Auto-Correlations and Frequency Spectra

In Figure 8 are shown the mathematical definitions of the auto-correlation function (ACF) and the frequency spectrum (FS). Suffice it to say that the ACF is the sum of the products of a function and the same function a given interval away; and that the FS yields the coefficients (amplitudes) of the spatial frequencies which comprise the surface profile. Note that the results of these calculations are not single numbers, but functions which may be presented in graphical form.

Figure 9 shows some simple profiles and their corresponding ACF and FS functions. It is obvious that the periodic nature of the profiles is immediately revealed, although in different ways, by the two functions. The first three profiles in Figure 10 correspond more closely to realistic surfaces. The first is like a fine ground surface, the second like machined surfaces. The value of the ACF in these cases lies in the facts that it yields the RMS directly and also qualitatively indicates the nature of the surface variations, differentiating between random and periodic components.

In Figure 11 are shown some of the results of one study of real surfaces wherein the peak height distribution, ACF and FS functions were computed. The problem with these higher order functions is that while they can differentiate types of surfaces, some means must be devised to associate index numbers with them and to relate these index numbers to product performance.

The Average Wavelength Parameter

A "wavelength-conscious" parameter which may be easily measured and describes in some degree roughness peak spacings has been suggested. The function being averages is the derivative (the instantaneous slope) of the profile; such an average may be done on an AA or RMS basis as indicated in Figure 12. The relation between the average wavelength and the RS for some real surfaces is shown in Figure 13. The parameter has the advantage that it may be measured by existing AA (or RMS) averaging instruments with only minor modifications or supplemental circuitry.

Summary of Parameter Characteristics

A table summarizing the characteristics of the surface parameters discussed above is given in Figure 14. The list is not meant to be inclusive but rather to point out that when measuring surfaces, one should be critically aware of what a measured parameter does (and does not) tell him about a surface.

As indicated, a topographical map is just so much raw data; it can be displayed to give a qualitative image or numerically analyzed. A profile is a two dimensional cross section of a surface; how well it represents the entire surface is a problem to contend with. Given a profile, the six index numbers and five functions are some of the means by which a profile can be analyzed. The profile details to which these parameters are sensitive are indicated; the degree to which these single parameter indices (or those which may come to be associated with the functions) are related to final product operation is another question.

Conclusion

In conclusion, it should be emphasized that carefully measured AA values may validly characterize one aspect of surface texture. Further, if AA specifications for surface finish are accompanied by a specification of the final process by which the surface if formed, control is placed over some of the other aspects which AA values do not reflect. However, in order that the periodic and random nature of a surface can be quantitatively described, new tools must be developed and evaluated.

Higher order mathematical descriptions of surfaces, achieved through computer analysis of profiles, may be a necessary and, in the long run, economical means of analyzing surface topography and relating it to product function and reliability. At present such analysis is practical only in a research environment and achievable at relatively high cost. However, it is likely that in the future blueprints will need to specify much more about a surface finish than one number can tell.

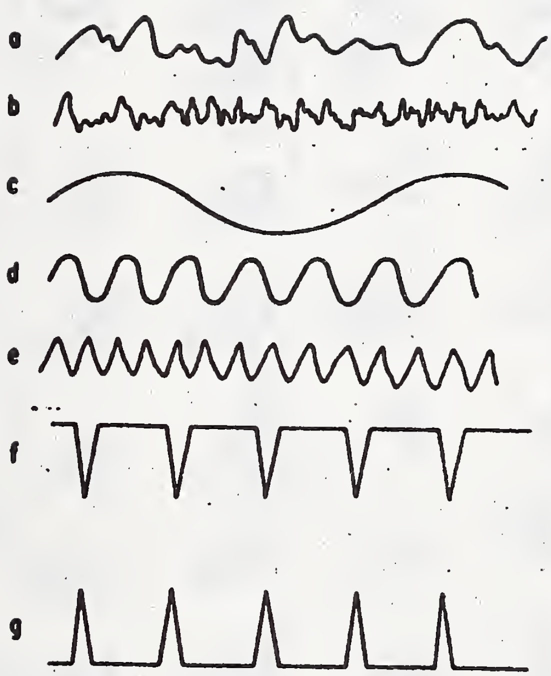
Figure Credits

Boundary Lubrication: An Appraisal of World Literature, ASME Research Committee on Lubrication, F. F. Ling, et al., eds., 1969, p. 9 (Figure 1).

Federal Scientific Corp., Tech. Notes on Ubiguitous Analyzer and Spectrum Analyzers. (Figures 9 - 10).

The Properties and Metrology of Surfaces, IME Conference Proceedings, Vol. 182, part 3K, 1967-68, p. 118-119 (Figure 11).

Measurement and Control, Vol. 5, March 1972, p. 98 (Figure 13).



—CENTER-LINE AVERAGE ROUGHNESS FOUND BY DRAWING LINE THAT CUTS OFF EQUAL AREAS ABOVE AND BELOW AND BY CALCULATING MEAN DEVIATION FROM THIS LINE [19]

FIGURE 1

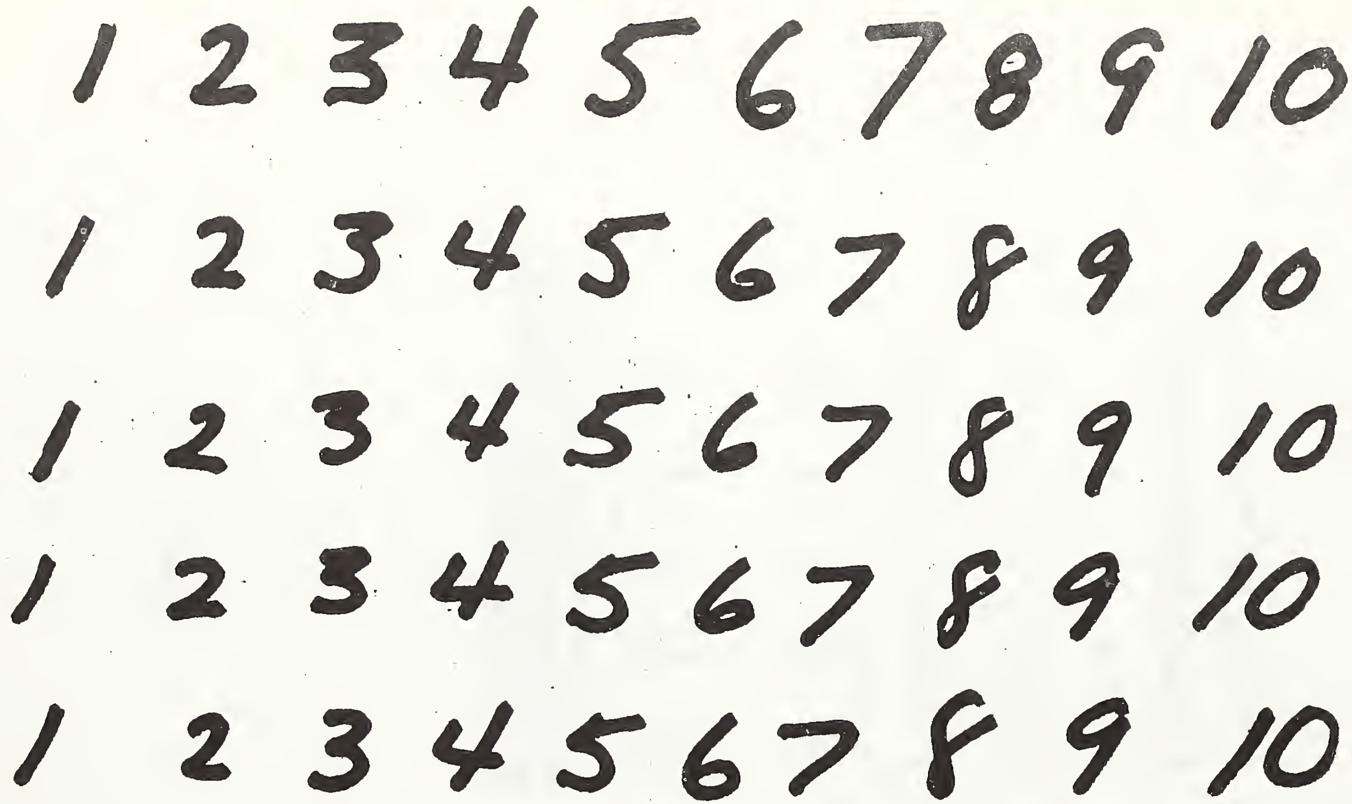

1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10

FIGURE 2

$$\text{AVERAGE (MEAN)} = \frac{\Sigma x}{N}$$

$$\text{AV. DEVIATION} = \frac{\Sigma \, \text{ABS} (x - \text{AV})}{N}$$

$$\text{STANDARD DEV} = \text{SQRT} \left[\frac{\Sigma (x - \text{AV})^2}{N - 1} \right]$$

$$\text{RANGE} = x_{MAX} - x_{MIN}$$

FIGURE 3

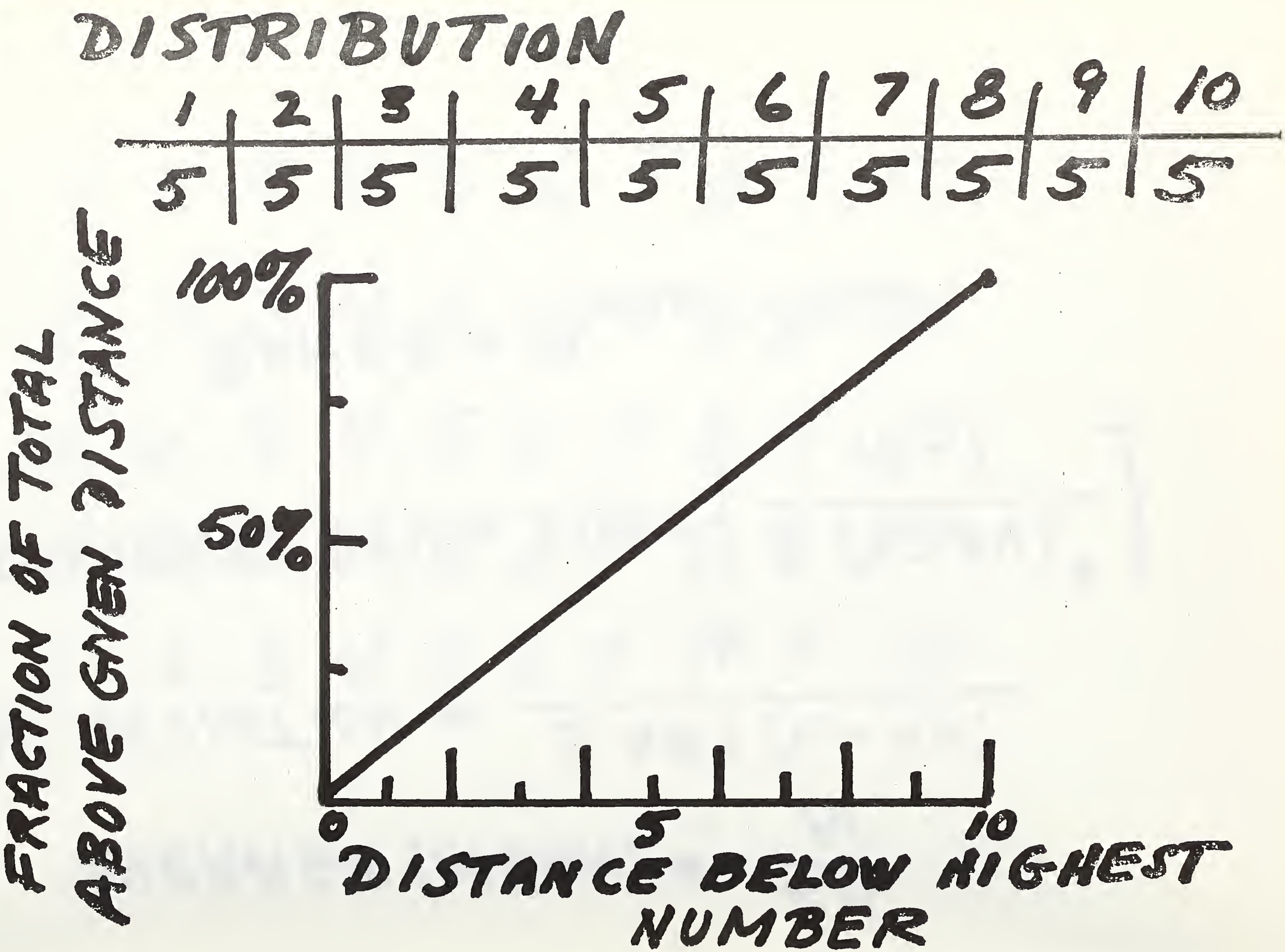

DISTRIBUTION
1 2 3 4 5 6 7 8 9 10
5 5 5 5 5 5 5 5 5 5
100%
50%
FRACTION OF TOTAL ABOVE GIVEN DISTANCE
0
5
10
DISTANCE BELOW HIGHEST NUMBER

FIGURE 4

AVERAGE = CENTER LINE

AV. DEVIATION = AA (CLA)

STANDARD DEV. = RMS

DISTRIBUTION CURVE =

BEARING AREA CURVE

RANGE = MAX. PEAK TO VALLEY DISTANCE

FIGURE 5

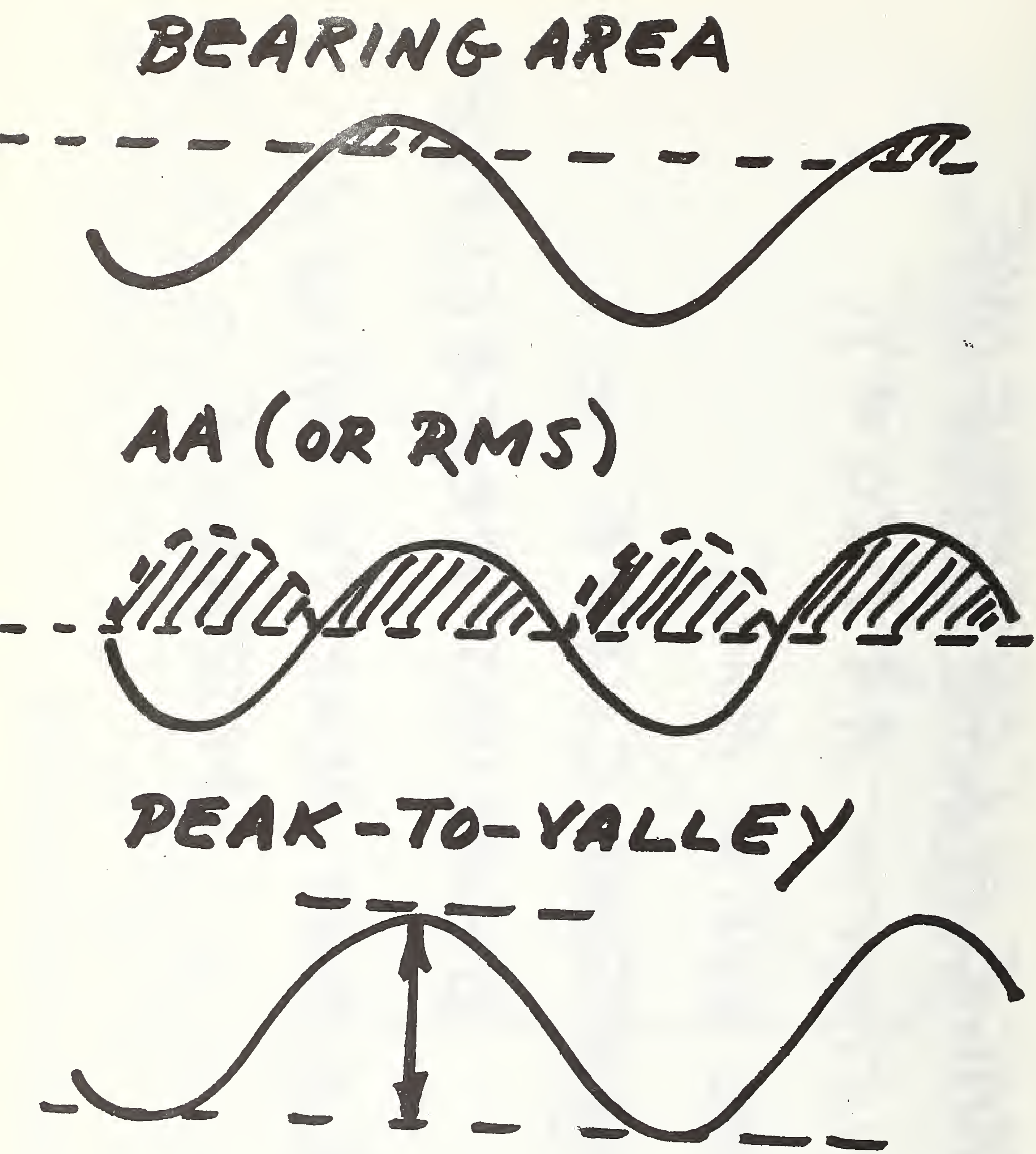


FIGURE 6

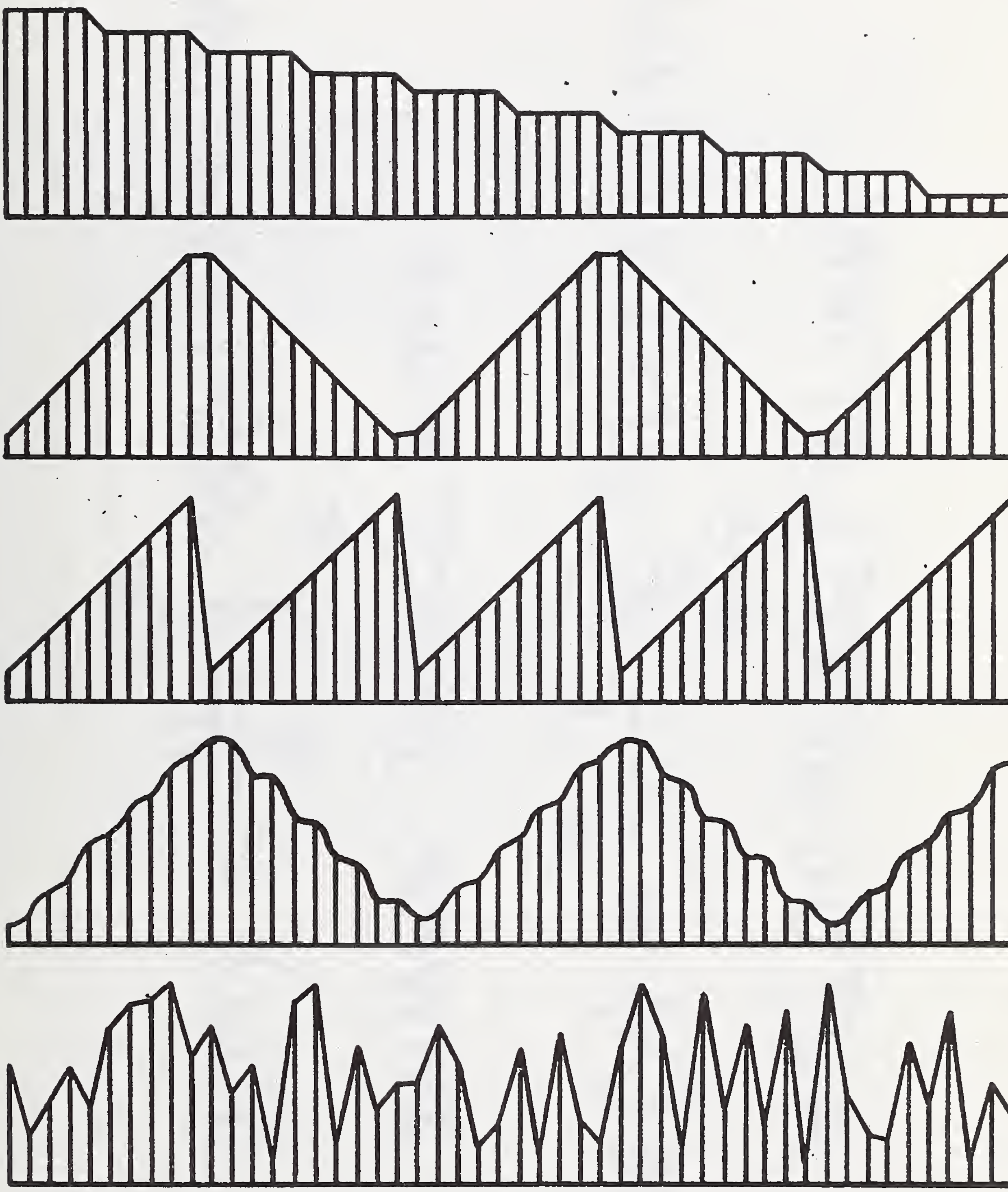


FIGURE 7

AUTOCORRELATION

$$R(\lambda) = \frac{1}{N-\lambda} \sum_{1}^{N-\lambda} y(x)\, y(x+\lambda)$$

POWER SPECTRUM

$$S(\omega) = \frac{2}{\pi} \int_{0}^{\infty} R(\lambda) \cos(\omega\lambda)\, d\lambda$$

FIGURE 8

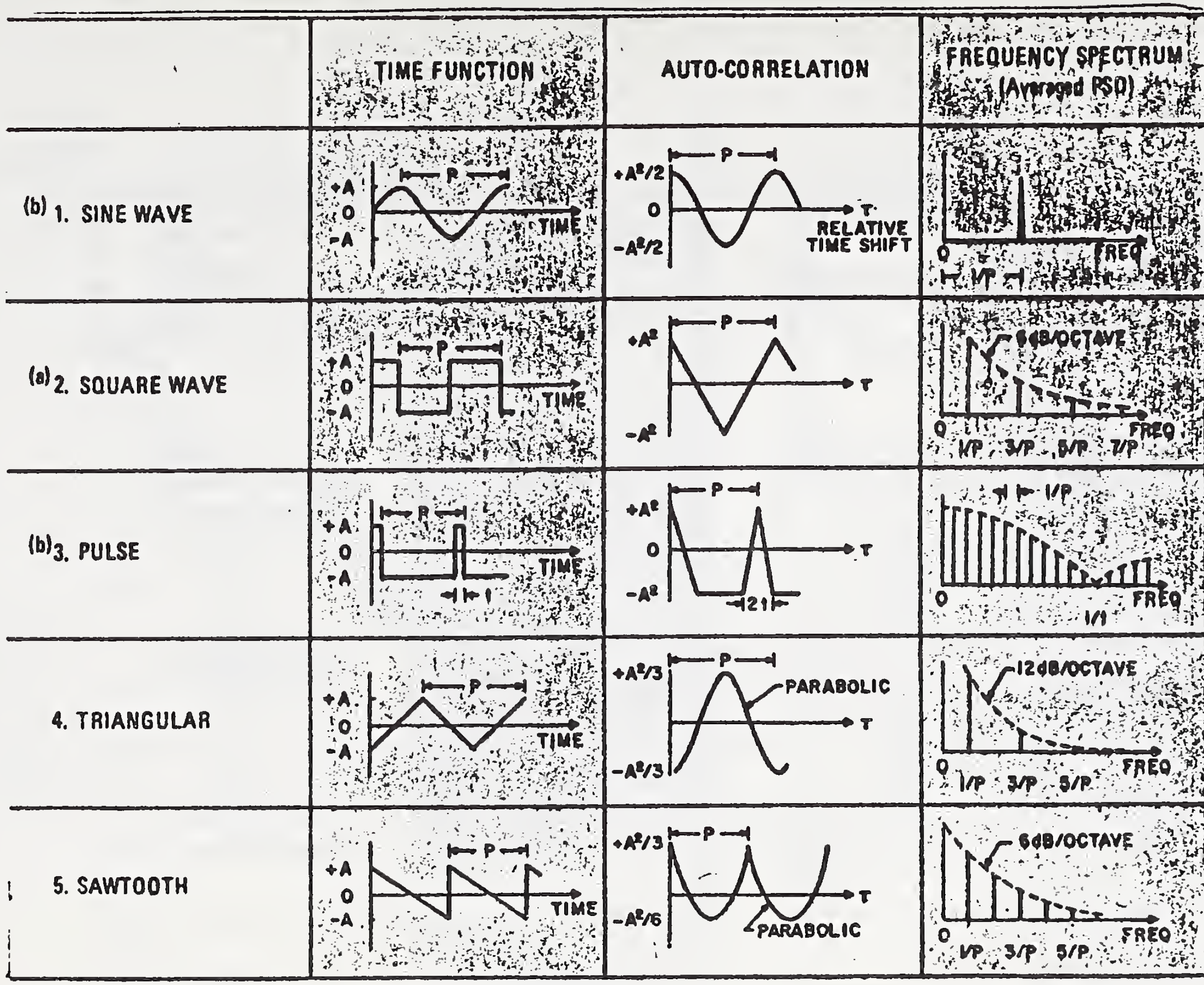
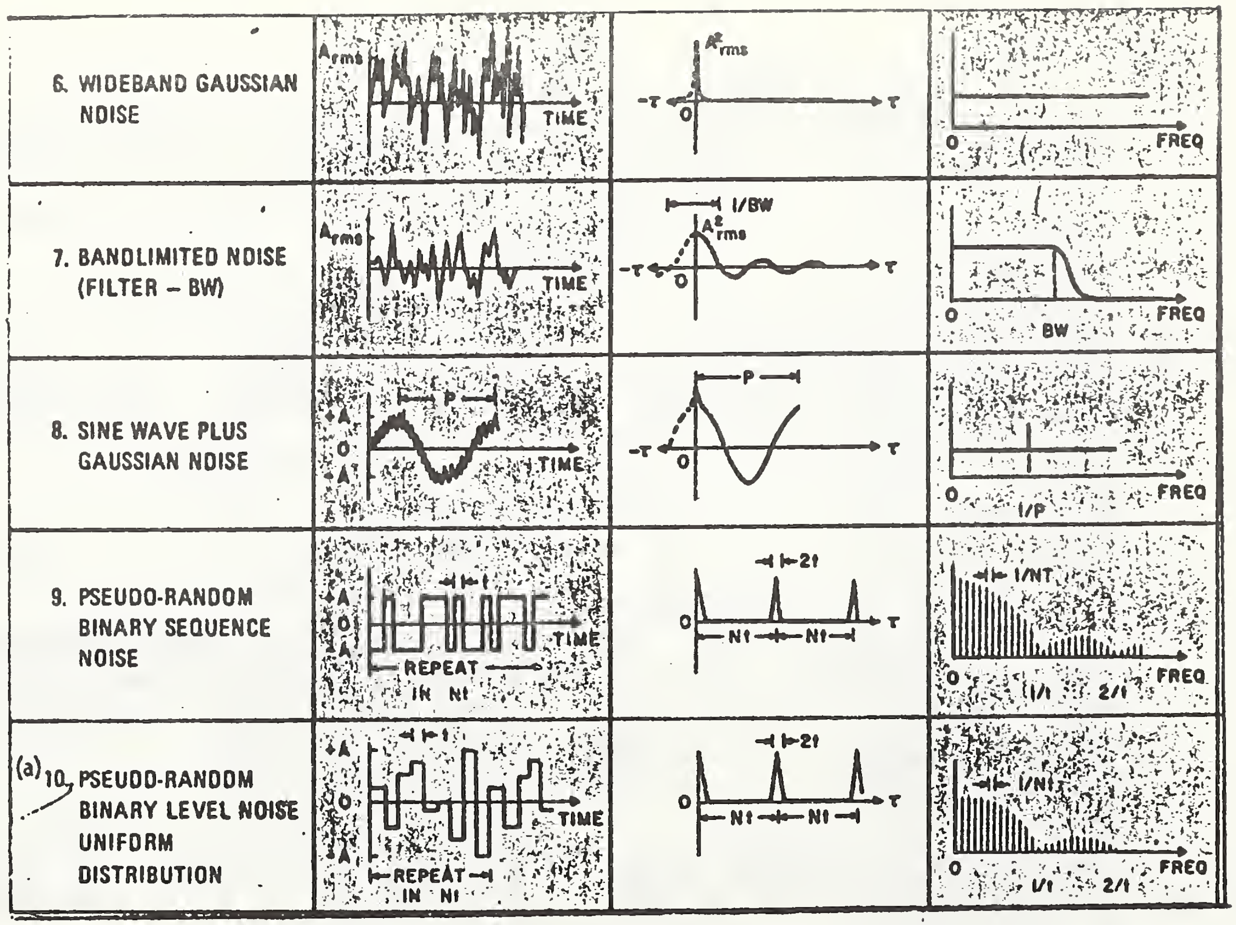
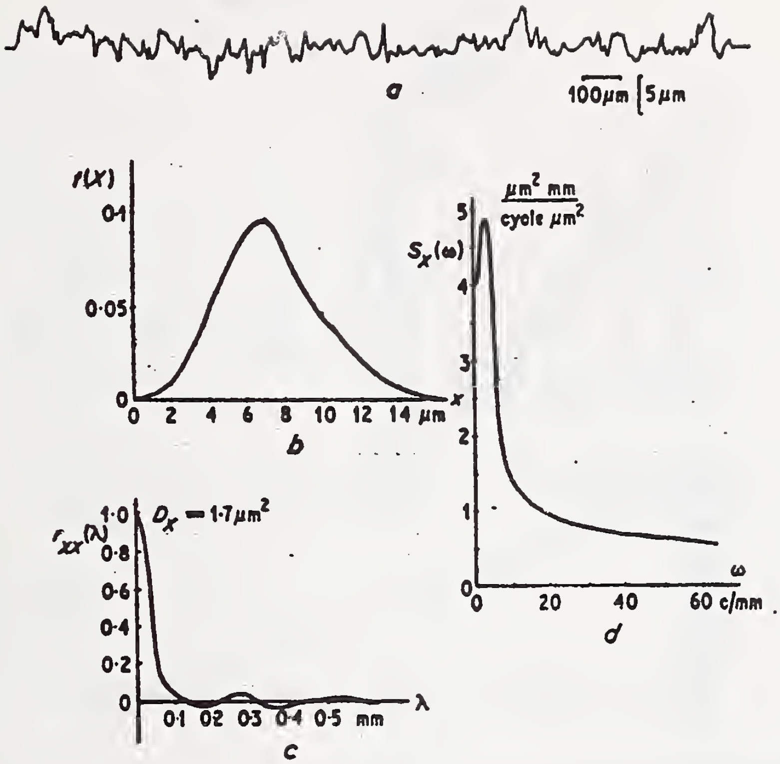

TIME FUNCTION
AUTO-CORRELATION
FREQUENCY SPECTRUM (Averaged PSD)
(b) 1. SINE WAVE
(a) 2. SQUARE WAVE
(b) 3. PULSE
4. TRIANGULAR
5. SAWTOOTH
+A
0
-A
TIME
P
+A²/2
-A²/2
RELATIVE TIME SHIFT
+A²
-A²
+A²/3
-A²/3
-A²/6
PARABOLIC
FREQ
6dB/OCTAVE
12dB/OCTAVE
1/P
3/P
5/P
7/P

FIGURE 9

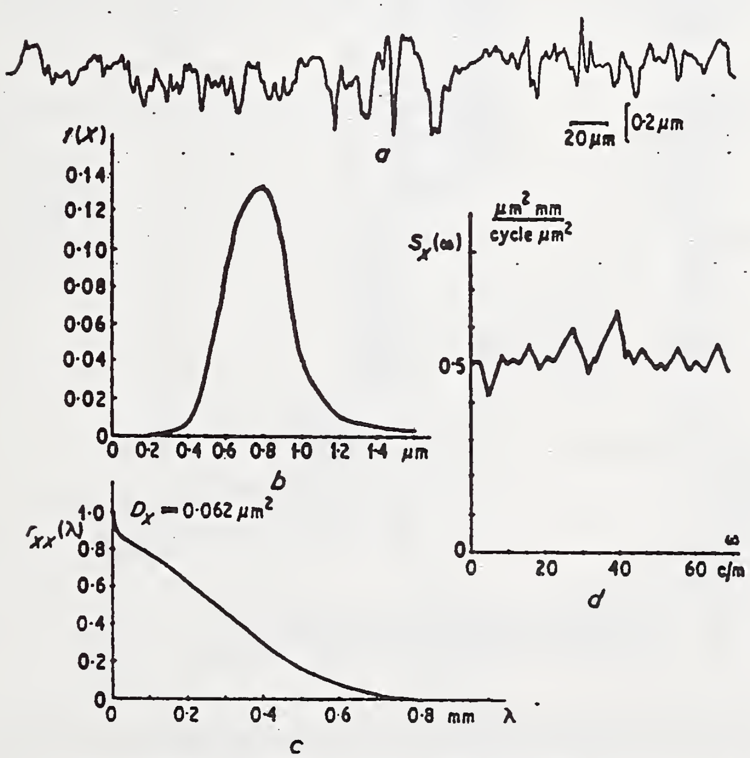


6. WIDEBAND GAUSSIAN NOISE
7. BANDLIMITED NOISE (FILTER – BW)
8. SINE WAVE PLUS GAUSSIAN NOISE
9. PSEUDO-RANDOM BINARY SEQUENCE NOISE
(a) 10. PSEUDO-RANDOM BINARY LEVEL NOISE UNIFORM DISTRIBUTION
TIME
FREQ
BW
1/BW
REPEAT IN Nt

FIGURE 10

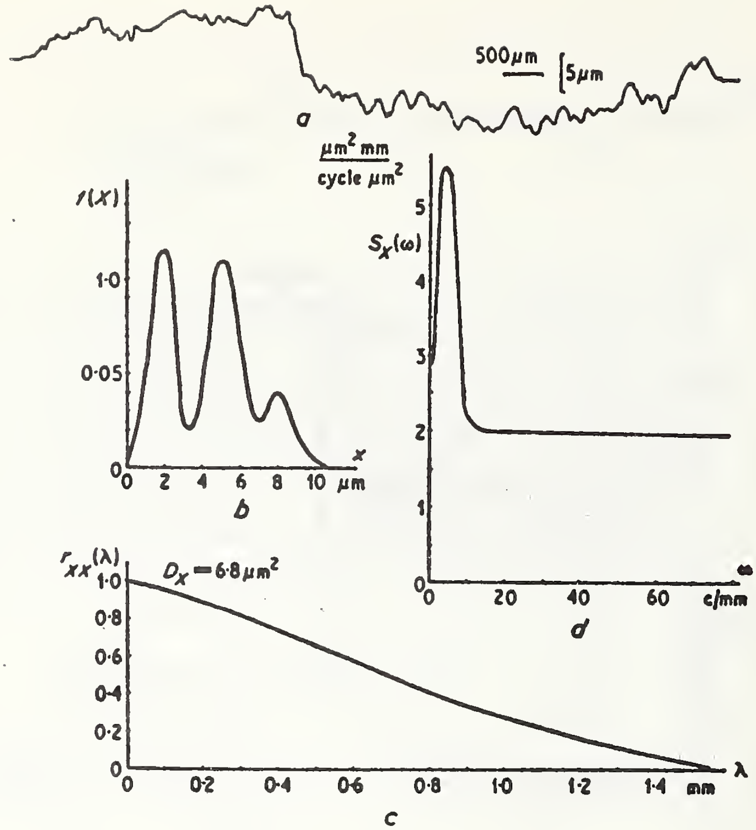


.. *Profilogram and characteristics of a surface-ground surface, c.l.a. = 1·0 µm*

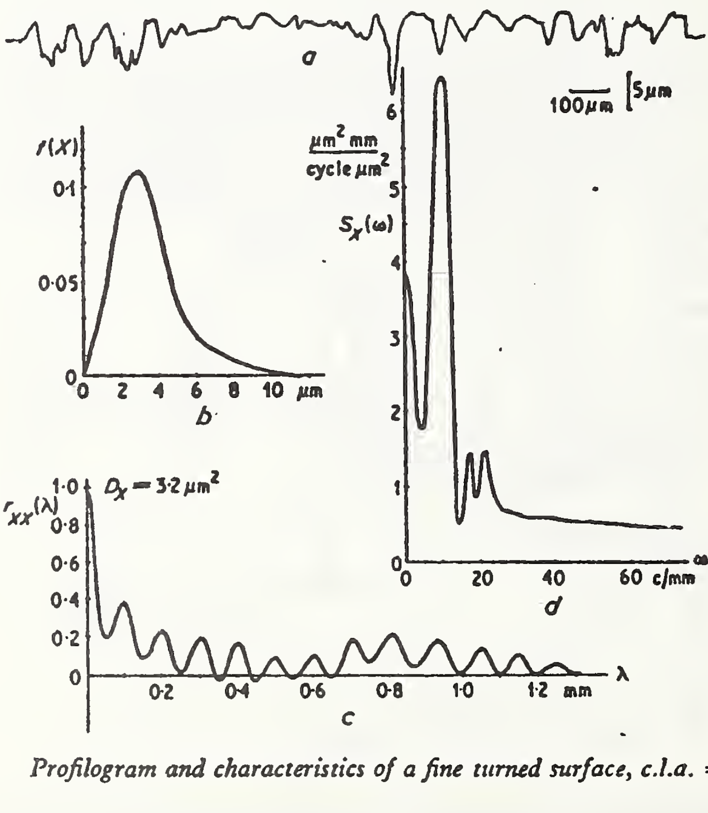


Profilogram and characteristics of a superfinished surface, c.l.a. = 0·18 µm

FIGURE 11a



Profilogram and characteristics of an electrolytic machined surface, c.l.a. = 2·2 μm



Profilogram and characteristics of a fine turned surface, c.l.a. = 1·4 μm

FIGURE 11b

	Average Slope	RMS Slope	Average* Wavelength	RMS Wavelength
Profile 2	0.9	0.95	17.5	19.8
Profile 3	1.8	3.0	8.8	6.3
Profile 4	0.9	1.3	17.5	14.5
Profile 5	3.6	4.5	4.5	4.2

* λ Average $= 2\pi \dfrac{\text{Average Roughness}}{\text{Average Slope}}$

AVERAGE SLOPE CHARACTERISTICS OF CONSTRUCTED PROFILES IN FIGURE 7

FIGURE 12a

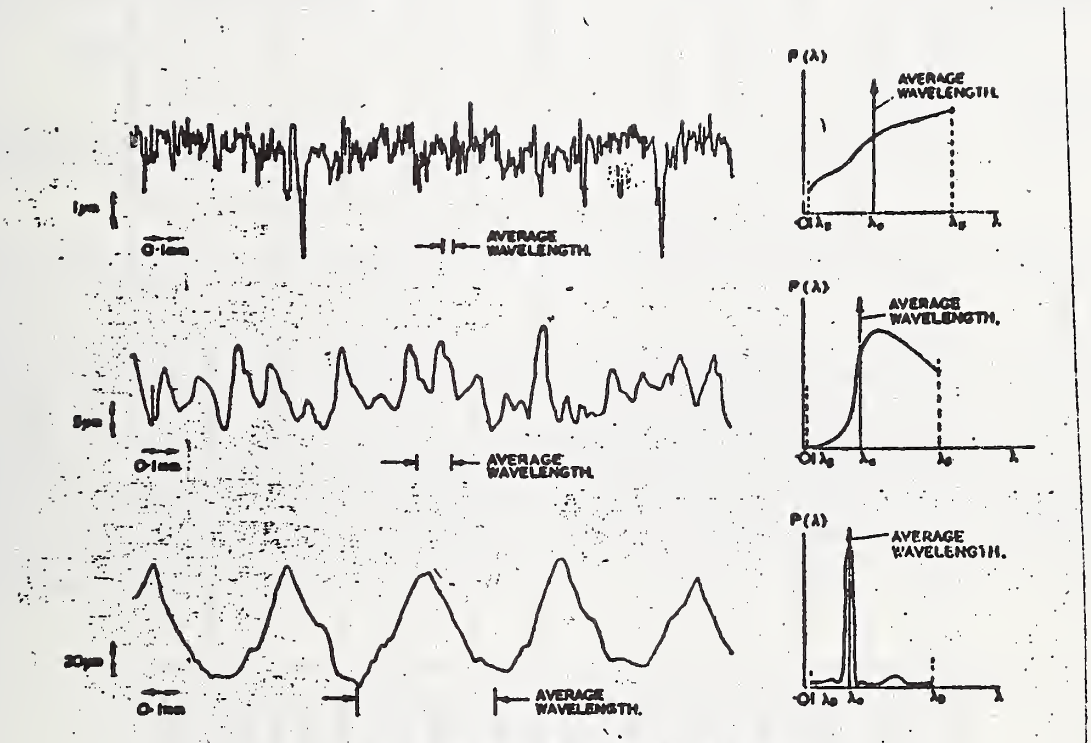
AVERAGE SLOPE

$$\overline{\tan\theta} = \frac{1}{L}\int_0^L \left|\frac{dy}{dx}\right| dx$$

AVERAGE WAVELENGTH

$$\lambda_{AV} = \frac{AA}{\overline{\tan\theta}} \text{ or } \frac{RMS}{\overline{\tan\theta_{RMS}}}$$

FIGURE 12



Power spectrum and average wavelength

FIGURE 13

CHARACTERISTIC	TYPE	HEIGHT			WAVELENGTH	
		MAX.	OCCURRENCE	SPATIAL DIST	DOMINANT	DISTRIBUTION
TOPOGRAPHICAL MAP	3D ARRAY					
PROFILE	2D ARRAY					
MAX. PEAK	INDEX	X				
TEN POINT PEAK-VALLEY	INDEX	X				
AA(CLA)	INDEX		X			
RMS	INDEX		X			
AVERAGE SLOPE	INDEX					X
AVERAGE WAVELENGTH	INDEX					X
PEAK DISTRIBUTION	GRAPH	X	X			
BEARING AREA	GRAPH	X	X			
FOURIER SPECTRUM	GRAPH				X	X
POWER DENSITY	GRAPH				X	X
AUTOCORRELATION	GRAPH		X	X	X	X

FIGURE 14

FORM NBS-114A (1-71)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Surface finish is most commonly described by an arithmetic average (AA) value, often coupled with a description of the process by which the surface is finally formed. Since the insensitivity of the AA parameter to the periodic nature of surface structure is well known, many supplemental "second" parameters have been suggested. This short paper gives an indication of the basis for the insensitivity of the AA parameter to periodic structure and considers briefly some "wavelength-conscious" parameters (e.g., average wavelength and correlation lengths) which may be useful in supplementing the basic AA value for a more complete description of surface finish.

17. KEY WORDS (Alphabetical order, separated by semicolons)
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