Surface Roughness Studies for Wind Tunnel Models Used in High Reynolds Number Testing

T. V. Vorburger,* M. J. McLay,† F. E. Scire,‡
D. E. Gilsinn,§ C. H. W. Giauque,‡ and E. C. Teague¶
National Bureau of Standards, Gaithersburg, Maryland

This paper focuses on stylus and optical techniques for the measurement of surface roughness in wind tunnel models. The stylus instruments provide detailed information, such as surface profiles and area maps, that may then be used either to calculate statistical properties (i.e., the rms surface roughness) or to study individual surface peaks or other features. By contrast, certain optical techniques yield area-averaged statistical properties of the surface roughness directly. Two instruments that use the technique of optical angular scattering are compared. One is a research instrument that has been developed to study the basic scattering phenomena by testing the optical theories and surface models used in inverse calculations of statistical roughness parameters. The second instrument is more compact and is under development as a hand held, on-line device to be used during manufacture of wind tunnel models for the National Transonic Facility at NASA Langley Research Center. The scattering geometries for the two instruments are compared and results from these instruments and the stylus technique are shown for roughness specimens that are typical of the surface finish of wind tunnel models.

Introduction

THE high Reynolds number flow conditions in the National Transonic Facility (NTF) require that models be fabricated with surface finishes smoother than normally required for conventional transonic wind tunnel testing. In order to prevent skin-friction penalties, admissible roughness heights may be as small as 0.20 μm (8 μin.) under extreme flow conditions in the NTF.[1] Therefore, it is important that transonic models be measured for surface roughness with high resolution in order to meet the required surface roughness criteria. However, the complicated shapes and large sizes make these models difficult to handle and measure with conventional stylus instruments.[2] Although such instruments have good accuracy and resolution, both vertical and horizontal, they are slow and difficult to align and, in normal operation, measure only two-dimensional profiles, thereby obtaining only vanishingly small samples of the surface topography.[3] This problem may be overcome by the topographic mapping technique,[4] whereby the stylus is scanned over the surface in a raster fashion to produce an area map of the surface roughness. However, this method is more time consuming than conventional profiling.

Optical scattering techniques have widespread interest and usefulness due to their nondestructive nature and potential for rapid measurements of surface roughness. The key problem for optical methods is one of optical modeling,[5] i.e., understanding how optical scattering approaches can lead to reliable, practical techniques for surface roughness measurement.[6] Consequently, an appreciable amount of research and development is required to understand the general phenomena of optical scattering from rough surfaces and the detailed applications to particular kinds of manufactured surfaces.

In cooperation with the NASA Langley Research Center, an optical scattering technique is being developed at the National Bureau of Standards (NBS) to measure the surfaces of models to be tested in the NTF. The work is focused in two areas: stylus measurements of the detailed topography of typical surface finishes produced on NTF models and research and development for a prototype optical scattering instrument to measure the roughness of models.

Stylus Measurements

Stylus profiling measurements were performed with a commercial[7] instrument** interfaced to a minicomputer.[8-10] As the stylus traverses the surface, its vertical motion is converted into a time-varying electrical signal that accurately represents the peaks and valleys of the surface profile. The electrical signal undergoes 12 bit analog-to-digital conversion (ADC) and yields a roughness profile consisting of 4000 digitized points that may be permanently stored on a magnetic disk. The system was used to measure three roughness specimens typical of NTF model finishes. In this application, the vertical resolution of the instrument was limited by the quantization increment of the ADC, which was approximately 1.2 nm. The instrumental noise itself is approximately 0.3 nm. The horizontal resolution was limited by the approximate 0.5 μm width of the stylus tip. The specimens were flat blocks with dimensions $15 \times 15 \times 5$ mm, machined from Nitronic 40 and 347 stainless steel and then hand-lapped to produce the final finish. These were identified as Nos. 14 (N40), 15 (347), and 13 (N40) with nominal rms roughnesses[11] R_q of 4, 8-10, and 16 μin. (0.1, 0.2-0.25, and 0.4 μm), respectively. Surface profiles were measured perpendicular to the lay direction generated by the hand-lapping process. The stylus instrument was calibrated in the vertical z direction by a comparison of the vertical displacements with that measured for a step whose height was calibrated by interferometry. The horizontal spacing of the digitized points was 0.375 μm and since there were 4000 of these, the total length of each profile was 1.5 mm. Ten profiles were measured on each specimen to develop good

Presented as Paper 85-0228 at the AIAA 23rd Aerospace Sciences Meeting, Reno, NV, Jan. 14-17, 1985; received April 11, 1985; revision received Aug. 16, 1985.

*Physicist, Center for Manufacturing Engineering. Member AIAA.
†Electrical Engineer, Center for Manufacturing Engineering.
‡Technician, Center for Manufacturing Engineering.
§Mathematician, Center for Manufacturing Engineering.
¶Physicist and Group Leader, Center for Manufacturing Engineering.

**Certain kinds of commercial equipment are identified in this article to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards nor does it imply that the equipment identified is necessarily the best for the purpose.

statistics. Some selected profiles are shown in Fig. 1. The average R_q values for these surfaces were 0.078, 0.20, and 0.32 μm. Three-dimensional surface topography maps were also measured for two of these surfaces with a two-axis stylus instrument. The apparatus[4] is shown schematically in Fig. 2. The stylus is scanned over the surface in a raster fashion to produce the surface map. After 12 bit ADC, the individual surface data points are compressed to have 8 bit resolution (256 quantization levels) and each map is stored as an array of 512×512 points. The maps may be visualized and evaluated by a set of image analysis software, with results similar to the intensity map shown schematically in Fig. 2 whereby each quantized value of profile height is proportional to a single-pixel intensity projected on a CRT monitor. The x and y displacements in the mapping instrument were calibrated by a laser interferometer measurement system.

Two intensity maps are shown in Figs. 3 and 4a and a pseudosolid image[12] showing perspective is given in Fig. 4b. The maps may be evaluated quantitatively by making area-averaged calculations of R_q and roughness average[11] R_a to characterize the deviations of the surface about the mean plane. In addition, the surface power spectral density (PSD) may also be calculated by a two-axis fast Fourier transform (FFT) algorithm. The resulting function resolves the original surface into its Fourier components in two directions.

The preliminary area-averaged R_q values are 0.07 and 0.17 μm, respectively, for the No. 14 and 15 surfaces, values that agree nicely with the profile averages of 0.078 and 0.20 μm. However, several places on the mapped surfaces have peaks considerably taller than the surrounding surface roughness. Even the fairly smooth surface 14 reveals two structures with peaks approximately 0.3 and 0.6 μm above the mean surface plane (arrows in Fig. 3). These peaks could produce significant aerodynamic effects on a wind tunnel model.

At this stage, it should be noted that knowledge of fluid drag over rough surfaces is based largely on conventions derived from the sand grain roughness experiments performed by Nikuradse over 50 years ago.[13,14] In particular, the admissible roughness estimated to be 8 μin. (0.2 μm) for extreme flow conditions in the NTF is essentially a peak-to-valley roughness parameter. For many types of finished metal surfaces, this quantity would be a factor of four or more larger than R_q. That implies that under extreme flow conditions the admissible R_q for an aerodynamically smooth model should be 0.05 μm or smaller. However, a mitigating factor here is the orientation of the surface roughness. The models are generally finished so that the lay of the surface is oriented along the direction of flow over the model surface; therefore, the roughness in the direction of flow is less than the roughness ordinarily measured perpendicular to the lay. This effect would tend to relax the specification on R_q. The net result of these offsetting factors is that the admissible R_q for wind tunnel models in the NTF may not be far different from the published specification[1] of 0.2 μm. However, the relationship of flow behavior to roughness for wind tunnel models should be studied through controlled experiment on real surfaces. Toward that end, the profiles and area maps (stored permanently on computer disks) yield detailed knowledge of the surface roughness topography of typical model surface finishes. The use of real surface data, rather than equivalent sand grain models, and the parameterization of roughness in terms of easily measurable quantities such as the rms roughness can pave the way for improved understanding of drag in aerodynamic flow past rough surfaces. Since these lapped surfaces are not isotropic, but rather have a strong lay pattern, the flow theory will have to take into account the angle between the lay direction and the flow direction as well as account for the aerodynamic effect of varying that angle.

Optical Techniques

A light scattering instrument is also being developed for rapid measurement of roughness after manufacture. In the course of this work, two different classes of problems need to

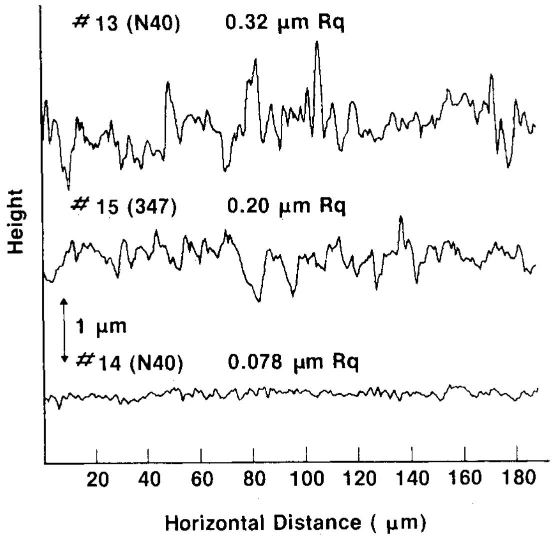


Fig. 1 Segments of surface profiles for NASA hand-lapped stainless steel specimens, measured by the stylus technique.

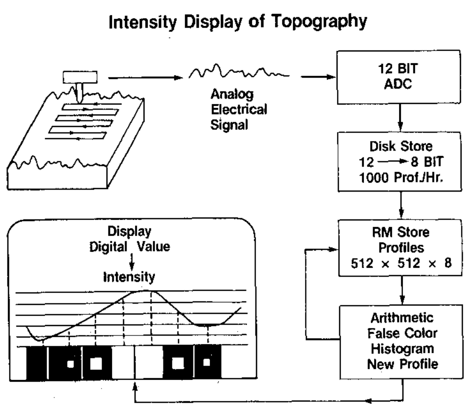


Fig. 2 Schematic diagram of the three-dimensional stylus instrument showing the process by which the surface topography of the specimens is transformed into an intensity image. RM is the refresh memory in the image analysis system.

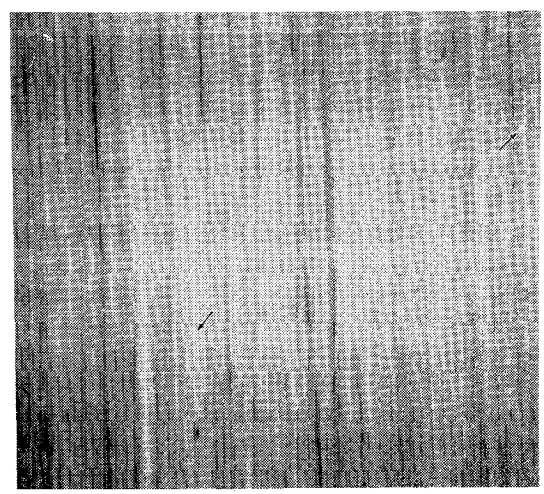


Fig. 3 Three-dimensional stylus profiling intensity map of hand-lapped stainless steel surface 14-N40. The area covered by the map is approximately 1 mm². The arrows show the positions of two high local peaks in the surface topography.

be solved:

1) The optical scattering and surface statistical models must be sufficiently well understood to enable calculation of surface topography parameters from angular scattering distributions.

2) The instrument must be adaptable for surface measurements on the complicated geometry of the models. Critical areas are the highly curved leading edges of the wings, where the specification of roughness is both important and difficult to measure. Therefore, the optical scattering instrument must be capable of proper alignment on surfaces with changing curvature and must be capable of separating any light spreading effects due to the surface curvature from those due to the roughness.

The prototype instrument being developed for this on-line application includes a hand-held, commercial[15] device** that contains a detector array to collect the angular distribution and an RS-232 computer interface. Software will be developed to process the information from the detectors to give the operator information concerning the proper alignment of the device with respect to the surface. The algorithms used with the prototype to compute surface texture parameters are being worked out with the help of an already developed research instrument called DALLAS[6] (detector array for laser light angular scattering), shown in Fig. 5. This apparatus includes a HeNe laser beam that is directed by a set of mirrors so that it illuminates a small area (of approximately 2 mm diameter) of the surface that is located at the center of a semicircular yoke of 87 detectors spaced 2 deg apart. The detectors collect the scattered light and transmit the signals by optical fibers to a photodiode array. The output voltages from the array are routed by a scanner to a digital voltmeter and then to a laboratory microcomputer. The resulting angular distributions (AD) may be used in a direct approach or an inverse approach to study optical scattering from rough surfaces.

In the direct approach, the ADs are compared with distributions calculated from profiles or maps measured directly by the stylus instrument. The detailed point-by-point information that is collected and stored by this stylus technique is operated upon by a suitable optical theory to produce the theoretical ADs. This approach bypasses surface modeling questions and directly tests the optical scattering theory itself. Comparisons between data and theory have been given previously.[6,16] In general, the agreement between theory and experiment is quite good. This suggests that a simple scalar theory of optical scattering, discussed previously,[6,16] may be sufficiently accurate to serve as a model for optical scattering phenomena in the engineering surface roughness regime (i.e., where rms roughness heights are the same order of magnitude as an optical wavelength and where the important surface spatial wavelengths are much greater than an optical wavelength). All of the surfaces tested so far were manufactured with a strong lay direction and, therefore, scatter light approximately into a plane rather than into the entire hemisphere above the surface. This allows for both experimental and theoretical[17-19] simplifications of the complex, vector electromagnetic scattering problem.[20,21] How well the scalar theory will do with rough, three-dimensional surfaces such as those produced by shot blasting remains to be seen.

a) 

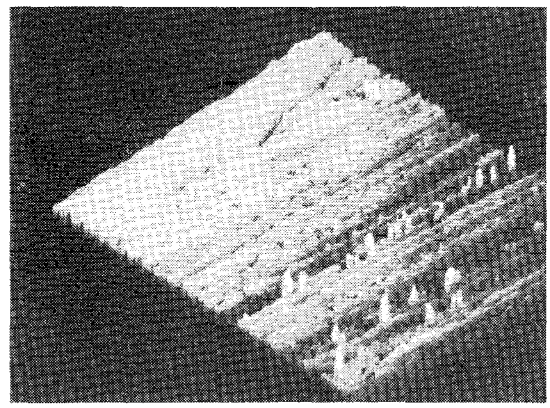
b) 

Fig. 4 a) Intensity map for the No. 15-347 specimen and b) pseudo solid image of a portion of the intensity map.

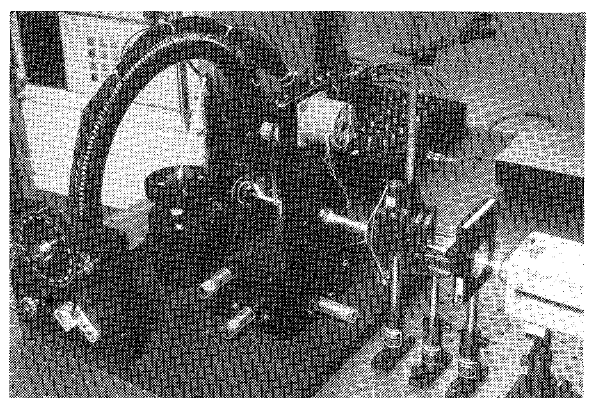


Fig. 5 DALLAS instrument; the laser beam is directed by two mirrors onto the surface of the specimen located at the center of the semicircular yoke supporting the detection system.

Table 1 Comparison of stylus and optical measurements of sinusoidal roughness parameters (all units in μm)[a]

Surface	Nominal		Parameters measured by stylus		Parameters deduced from optical technique	
	R_q	D	R_q	D	R_q	D
Brass	1.11	40	1.14±0.03	40.1±0.4	1.129±0.003	39.89±0.03
Brass	1.11	100	1.13±0.03	100.2±0.4	1.117±0.003	99.6±0.2
Nickel	1.11	100	1.14±0.03	100.2±0.4	1.123±0.002	100.2±0.3
Nickel	0.33	100	0.35±0.02	100.2±0.4	0.348±0.004	100.8±0.7
Nickel	3.33	100	3.32±0.05	100.1±0.4	3.32±0.06	99.3±1.3

[a]Uncertainties in the stylus results represent estimates of both random and systematic errors. Uncertainties in the optical results represent estimates of random errors only.

The inverse approach is used to estimate the statistical roughness parameters themselves. Now, instead of measuring the surface topography by a stylus instrument, the surface is modeled with appropriate statistical functions that contain variable parameters such as the rms roughness and the autocorrelation length. The resulting theoretical AD is fitted to the data and the best fit yields estimates of the surface parameters. The accuracy of the approach is tested by the agreement between the theoretical and experimental ADs and by the agreement between the best fit parameters and those calculated from the stylus instruments.

The inverse approach has been used in experiments on sinusoidal surfaces.[16,22,23] The highly periodic nature of these surfaces leads to a set of intense diffraction beams in the AD, as shown in Fig. 6. In order to resolve the closely spaced diffraction peaks, the DALLAS apparatus was operated in a high-resolution mode. The laser itself was positioned so that it illuminated the sample directly, without mirrors, at an angle of incidence of 45 deg orthogonal to the yoke plane. The detector at the top of the yoke was apertured by a 1 mm slit so that the effective detector width was 0.35 deg. By rotating the yoke the detector was then swept through the scattering pattern to produce a high-resolution AD.

The ADs may be fitted to the theoretical calculations to estimate the amplitude and wavelength parameters of the sine wave on each surface. Five sinusoidal surfaces have been tested with nominal values for R_q and wavelength D shown in columns two and three of Table 1. The stylus measurements of R_q and D are shown in columns 4 and 5. The surface model for the inverse calculation contained the sine wave amplitude A and wavelength D as variable parameters. This surface model was then substituted into an optical scattering integral to yield a theoretical AD whose fit to the data in turn yielded the best estimates of the two parameters. A typical best fit is shown in Fig. 6. R_q was then calculated from A by the relation $R_q = A/\sqrt{2}$, which holds exactly for a sine wave. The resulting optical measurements of R_q and D (shown in far right columns of Table 1) agree quite well with the stylus values. The uncertainties quoted for the stylus results are estimates of 68% confidence intervals that take into account both random and systematic uncertainties and are based on long-term experience with stylus methods.[8,24] The uncertainties quoted for the optical results are smaller because they represent estimates of random uncertainty based only on statistical models[22] and do not take into account systematic uncertainties in either the experiment or the theoretical model.

These results support the validity of the scalar optical theory when applied to sinusoidal surfaces. It should be noted once again that these surfaces had a strong lay direction and were, therefore, highly two-dimensional.

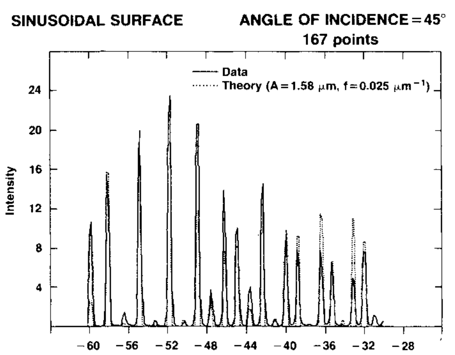
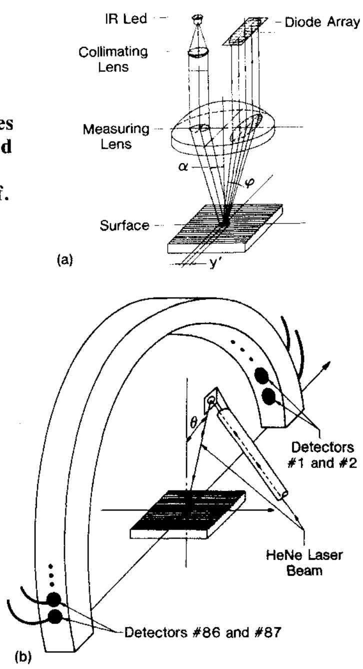


Fig. 6 Typical fit between the experiment and the theoretical model for the angular scattering distribution from a sinusoidal surface with amplitude $A = 1.58$ μm and wavelength $D = 40$ μm (spatial frequency $f = D^{-1}$). The surface was oriented so that all of the diffraction peaks were scattered and detected in the plane of incidence. See Refs. 16 and 22. The angle of incidence was +45 deg, so the specular beam was located at a scattering angle of −45 deg.

We now turn to preliminary measurements with the on-line instrument of the NASA surfaces 13-15 discussed above. These measurements are qualitatively compared with the R_q results from stylus profiling and the results from DALLAS. The scattering geometry of the on-line instrument is somewhat different from that of the DALLAS instrument (Fig. 7). In both cases, the surface is oriented in such a way that the detector array intercepts the planar pattern of scattered light. The on-line instrument has been discussed by Brodmann, et al.[25,26] and is shown schematically in Fig. 7a. It consists of an optical source with an infrared wavelength of about 800 nm and a 20 detector photodiode array that spans a scattering angle (2ϕ) of 30 deg. The angle of incidence α is equal to 8.4 deg, just far enough off normal so that the optics for collecting the scattered radiation do not interfere with the incident beam. The illumination spot diameter y' is approximately 1.8 mm. Under proper alignment, the long axis of the detector array is parallel to the roughness direction on the surface, i.e., perpendicular to the lay of the machining marks.

In the DALLAS setup, the angle of incidence θ, which may be varied, was set at 40 deg and the roughness direction and the plane of the semicircular detector yoke were oriented in the plane of incidence. The detector yoke consists of 87 detectors separated by 2 deg, spanning a total angle of ±86 deg with

Fig. 7 a) Scattering geometries for the on-line instrument and b) the Dallas instrument (diagram a is taken from Ref. 26).



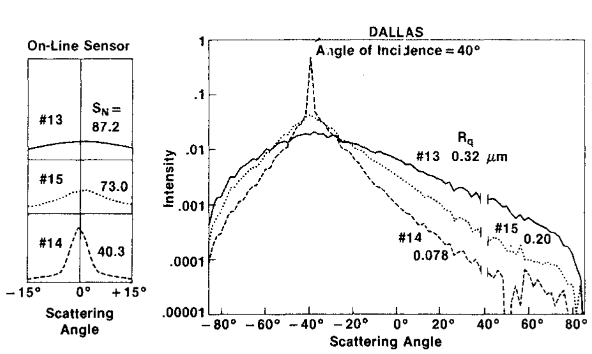


Fig. 8 Measured optical ADs with the on-line sensor (left) and the DALLAS instrument (right) for the stainless steel roughness specimens 13, 15, and 14. The DALLAS data are plotted on a logarithmic scale that spans five orders of magnitude, whereas the data for the on-line instrument are plotted linearly with intensity. The results from the on-line sensor include a scattering index S_N that is proportional to the variance of the scattering pattern about the mean.

respect to the surface normal. Therefore, the angular range of the DALLAS detection system is a little less than three times that of the on-line instrument.

The two sets of angular scattering results are shown in Fig. 8 and these may be correlated with the stylus profiles of Fig. 1. As the rms roughness increases, the angular scattering pattern broadens for both instruments. In particular, the DALLAS result for surface 14 with 0.078 μm R_q clearly shows a strong specular beam at a scattering angle of -40 deg. This peak disappears as the diffuse scattering curve broadens for the two rougher surfaces. The on-line sensor data do not show a narrow specular beam because the angular resolution of this instrument is broader, owing to the finite convergence angle of the incident beam. Nevertheless, these scattering patterns also show increasing width as R_q increases. In addition, a scattering pattern index, known as S_N, tracks the R_q roughness values. S_N is a nonstandard parameter, introduced by the manufacturer of the on-line instrument, that is directly proportional to the variance of the bell-shaped scattering pattern. In Fig. 8, the S_N value tends to increase with the rms roughness. Figure 8, therefore, shows a clear correlation between roughness and scattering for this small number of specimens and this correlation may be exploited to develop an on-line instrument to measure roughness of NTF models.

Summary and Future Directions

Stylus and optical scattering measurements have been taken on hand-lapped stainless steel (SS) surfaces and on sinusoidal surfaces in order to characterize the surface roughness of wind tunnel models. Stylus maps of the SS surfaces reveal interesting features that could produce significant aerodynamic effects on a wind-tunnel model, and the stylus profiles provide a good metrological basis for studying optical scattering by rough surfaces. Optical scattering experiments on sinusoidal surfaces yield values for the surface wavelength and rms roughness that agree very well with those obtained by the stylus.

For three SS surfaces of varying roughness, the rms roughness values measured by the stylus method correlate very well with the changes in the optical scattering distributions measured both by a high-resolution research instrument and a commercial, on-line sensor.

Future work in this area will have three major thrusts: 1) research into the surface topography of the models by stylus techniques, 2) research on the appropriate model for optical scattering, and 3) development of the on-line instrument for use with NTF models.

The future research on optical scattering will initially involve direct scattering calculations of angular distributions from the NASA stainless steel specimens using stylus profiling data for these surfaces. These ADs will be compared with the experimentally measured ADs obtained either with DALLAS or with the on-line instrument. Then various surface statistical models will be tested in inverse scattering calculations to derive useful surface roughness parameters. For these stainless steel specimens, the important parameters will likely be the rms roughness R_q and the autocorrelation length of the surface features.[11,17]

Both the digitized stylus data and the optical scattering technique yield considerably more information about the surface topography than the single sand grain roughness parameter developed by Nikuradse. In particular, the stylus data enable the calculation of surface slopes, curvatures, and statistical functions like the power spectral density of spatial frequencies[27,28] as well as the traditional roughness height parameters. Experiments to relate real surface topography parameters to aerodynamic flow over rough surfaces could lead to significant development in the specification of aerodynamic finish. Experiments along these lines have already been performed for hydrodynamic applications.[29-31]

Acknowledgments

This work was supported in part by NASA Langley Research Center under Contract L4718B, by the NBS Office of Nondestructive Evaluation, and by the Navy Materiel and Air and Sea Systems Commands. We thank V. S. Gagne and S. A. Morris for assistance in the preparation of the manuscript.

References

[1]McKinney, L.W., "Overview of National Transonic Facility Model Technology Program," *Cryogenic Wind Tunnel Models, Design and Fabrication,* edited by C.P. Young, Jr. and B.B. Gloss, NASA CP 2262, 1983, pp. 1-9.

[2]Thomas, T.R., "Stylus Measurements," *Rough Surfaces,* edited by T.R. Thomas, Longman, London, 1982, Chap. 2, pp. 12-41.

[3]Vorburger, T.V. and Teague, E.C., "Optical Techniques for On-Line Measurement of Surface Topography," *Precision Engineering,* Vol. 3, April 1981, pp. 61-83.

[4]Teague, E.C., Scire, F.E., Baker, S.M., and Jensen, S.W., "Three-Dimensional Stylus Profilometry," *Wear,* Vol. 83, 1982, pp. 1-12.

[5]Teague, E.C., Vorburger, T.V., and Maystre, D., "Light Scattering from Manufactured Surfaces," *Annals of the CIRP,* Vol. 30, No., 2, 1981, pp. 563-569.

[6]Vorburger, T.V., Teague, E.C., Scire, F.E., McLay, M.J., and Gilsinn, D.E., "Surface Roughness Studies with DALLAS-Detector Array for Laser Light Angular Scattering," *Journal of Research of the National Bureau of Standards,* Vol. 89, Jan.-Feb. 1984, pp. 3-16.

[7]Talystep stylus instrument, distributed by Rank Precision Industries, Des Plaines, IL.

[8]Teague, E.C., "Evaluation, Revision, and Application of the NBS Stylus/Computer System for the Measurement of Surface Roughness," National Bureau of Standards Tech. Note 902, April 1976.

[9]Vorburger, T.V., Teague, E.C., Scire, F.E., "Fast Facility Available for Engineering Needs," *Dimensions/NBS,* Vol. 62, Nov. 1978, pp. 18-19.

[10]Vorburger, T.V., "FASTMENU: A Set of FORTRAN Programs for Analyzing Surface Texture," National Bureau of Standards Internal Rept. 83-2703, July 1983.

[11]The rms roughness R_q and other surface parameters are defined in: American National Standards Institute B46.1-1978, "Surface Texture," American Society of Mechanical Engineers, New York, 1978.

[12]Gilsinn, D.E., "Solid-A FORTRAN Program for Displaying Three-Dimensional Surface Topographies," National Bureau of Standards Internal Rept. 85-3121, June 1985.

[13]Schlichting, N., *Boundary Layer Theory,* 7th ed., translated by J. Kestin, McGraw-Hill Book Co., New York, 1979, p. 616.

[14]Lewkowicz, A.K. and Musker, A.J., "The Surface Roughness and Turbulent Wall Friction on Ship Hulls: Interaction in the Viscous Sublayer," *International Symposium on Ship Viscous Resistance,* SSPA, Göteborg, Sweden, 1978, pp. 10:1-10:22.

[15]RM-400, distributed by Rodenstock Precision Optics, Rockford, IL.

[16]Gilsinn, D.E., Vorburger, T.V., Scire, F.E., Teague, E.C., and McLay, M.J., "Surface Characterization by Angular Distributions of Scattered Light," *Review of Progress in Quantitative NDE,* edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1985, pp. 779-788.

[17]Beckmann, P. and Spizzichino, A., *The Scattering of Electromagnetic Waves from Rough Surfaces,* Pergamon Press, New York, 1963, Chap. 5.

[18]Azzam, R.M.A. and Bashara, N.M., "Polarization Characteristics of Scattered Radiation from a Diffraction Grating by Ellipsometry with Application to Surface Roughness," *Physical Review,* Vol. B5, June 15, 1972, pp. 4721-4729.

[19]Vorburger, T.V. and Ludema, K.C., "Ellipsometry of Rough Surfaces," *Applied Optics,* Vol. 19, Feb. 15, 1980, pp. 561-573.

[20]Elson, J.M. and Bennett, J.M., "Vector Scattering Theory," *Optical Engineering,* Vol. 18, March-April 1979, pp. 116-124.

[21]Church, E.L., Jenkinson, H.A., and Zavada, J.M., "Measurement of the Finish of Diamond-Turned Metal Surfaces by Differential Light Scattering," *Optical Engineering,* Vol. 16, July-Aug. 1977, pp. 360-374.

[22]Gilsinn, D.E. Vorburger, T.V., Teague, E.C., McLay, M.J., Giauque, C., and Scire, F.E., "Surface Roughness Metrology by Angular Distributions of Scattered Light," *Measurement and Effects*

of Surface Defects and Quality of Polish, Proceedings of the SPIE, Vol. 525, 1985, pp. 2-15.
[23]Teague, E.C., Scire, F.E., and Vorburger, T.V., "Sinusoidal Profile Precision Roughness Specimens," *Wear,* Vol. 83, 1982, pp. 61-73.
[24]Teague, E.C., "Uncertainties in Calibrating a Stylus Type Surface Texture Measuring Instrument with an Interferometrically Measured Step," *Metrologia,* Vol. 14, 1978, pp. 39-44.
[25]Brodmann, R., Gast, Th., and Thurn, G., "An Optical Instrument for Measuring the Surface Roughness in Production Control," *Annals of the CIRP,* Vol. 33, No. 1, 1984, pp. 403-406.
[26]Brodmann, R., Gerstorfer, O., and Thurn, G., "Optical Roughness Measuring Instrument for Fine-Machined Surfaces," *Optical Engineering,* Vol. 24, May-June 1985, pp. 408-413.
[27]Church, E.L., Howells, M.R., and Vorburger, T.V., "Spectral Analysis of the Finish of Diamond-Turned Mirror Surfaces," *Reflecting Optics for Synchrotron Radiation, Proceedings of the SPIE,* Vol. 315, 1982, pp. 202-218.
[28]Church, E.L., Vorburger, T.V., and Wyant, J.C., "Direct Comparison of Mechanical and Optical Measurements of the Finish of Precision Machined Optical Surfaces," *Optical Engineering,* Vol. 24, May-June 1985, pp. 388-395.
[29]Vorburger, T.V., Scire, F.E., and Teague, E.C., "Hydrodynamic Drag Versus Roughness for Rotating Disks," *Wear,* Vol. 83, 1982, pp. 339-349.
[30]Musker, A.J. and Lewkowicz, A.K., "The Effect of Ship Hull Roughness on the Development of Turbulent Boundary Layers," *International Symposium on Ship Viscous Resistance,* SSPA, Göteborg, Sweden, 1978, pp. 11:1-11:20.
[31]Karlsson, R.I., "The Effect of Irregular Surface Roughness on the Frictional Resistance of Ships," *International Symposium on Ship Viscous Resistance,* SSPA, Göteborg, Sweden, 1978, pp. 9:1-9:20.