QUALITY CONTROL APPLICATIONS OF "DISCRIMINATION" TECHNOLOGY DEVELOPED FOR THE STRATEGIC DEFENSE INITIATIVE

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INTRODUCTION

The goal of the QNDE program at Nichols Research Corporation is to make 100% inspection practical on the production line for high-quality products such as precision ceramic ball bearings. The underlying methodology is to use analytical tools, both theoretical and experimental, for designing and engineering systems with predictable cost and effectiveness. Many of these tools have been developed in the course of our discrimination work on the Strategic Defense Initiative (SDI).

Generalized statistical pattern recognition techniques, on which the SDI discrimination technology is based, are applicable to many sensors and combinations of sensors. Since Nichols specializes in optical systems engineering, optical sensors were chosen as the first application of the SDI discrimination technology to production QNDE. That is the subject of this paper, which reports experimental results and analysis of the use of optical sensors to detect flaws on the surface of ceramic rolling element bearings.

Rolling element bearings are sensitive to surface defects that can be detected by optical sensors, since the primary mode of failure is spalling contact fatigue which originates with a defect at or near the surface. Steel bearings also have the same mode of failure, but the acceptable defect size must be more rigorously controlled in ceramics because the fracture toughness of ceramics is lower than that of steel. [1,2].

The following sections describe scattering and imaging data that has been obtained on ceramic specimens, and the application of statistical pattern recognition tools used in support of SDI discrimination technology. Up to this point, both the experimental data and the development of an application to QC is preliminary and heuristic. The data is still limited and not systematic enough to serve as a basis for conclusions about the viability of the approach. Nevertheless, the results presented below do afford significant reason to be encouraged in proceeding further along the same lines.

STATISTICAL ANALYSIS FOR ENGINEERING NDE SYSTEMS

KENN Code software [3] is a key tool used by Nichols to assist in a) developing classification algorithms that can be easily automated, and b) to express the performance of a classification system in terms of its physical characteristics. The physical characteristics of the system are determined by the data processing capability for implementing a particular classification algorithm; the sensors (e.g. detector size, focal length, aperture, etc.); the nature of the background, and artifacts of the sensor such as might be imposed, for example by a limited dynamic range; the signature-or characteristic attributes-of the unflawed objects as revealed by the sensor data; and the signature of the flawed objects.

The performance of the system is characterized by a function expressing the relationship between two quantities, PFP and PFF:

a) PFP is the "probability of false pass" of a flawed object "leaking" through the QC system. This corresponds to the term "Probability of Leakage," used in ballistic missile defense to express the probability that a lethal object is misclassified as non-lethal.
b) PFF is the "probability of false fail" i.e., that an unflawed object will be rejected. This corresponds to the term "Probability of False Alarm," used in ballistic missile defense to express the probability that an unarmed decoy is misclassified to be lethal.

Figure 1 illustrates how an NDE classification system is characterized by a relation between PFP and PFF. In the case used for illustration, the single signature parameter--with different mean values, but the same standard deviation, for flawed and unflawed objects--has a Gaussian distribution. (The simplifying approximations used in the illustration are not used in the actual data analysis.) The signature parameter in this case might be, for example, the peak value for the intensity gradient of scattered light on a sample. In an actual case, features of the measurements are characterized by a signature vector that may be made up of several parameters, e.g., maximum intensity difference, minimum intensity, etc.

The performance of the system in Fig. 1 can be characterized by the so-called Bhattacharyya distance which is, in effect, the normalized distance between the mean values of the signatures. For example, if the Bhattacharyya distance equals 3, the probability of passing a flawed part, PFP, is less than 0.5%, at the same time that the probability of passing an unflawed part, PFF, is less than 1%. If the level of system effectiveness is unchanged, reducing PFP to 0.1% will raise PFF to about 3%. (Coordinates scaled by the normal distribution error function yields the straight lines corresponding to a given value of Bhattacharyya distance shown.)

Reducing PFP without increasing PFF requires an improvement in the system, i.e. increasing the Bhattacharyya distance. This might be done by modifying the classification algorithm, increasing sensor resolution, or the number of samples per specimen. This type of analysis is essential in engineering discrimination systems for SDI, evaluating alternatives, and assessing cost effectiveness. It is equally valuable for NDE.

The KENN code, for which the preceding analysis is a special case that can be derived analytically, is applicable to non-parametric statistics and multidimensional signature vectors. The software incorporates tools for manipulating data, extracting critical features of signatures, performing analyses to optimize classification, and determining the PFP/PFF relationship [3,4].

APPLICATION OF KENN TO VIDEO IMAGING

Details of the application of KENN to a four-dimensional set of data from ceramic ball bearings is reported in [5]. Specimens were placed in the near field (approximately 4 cm from the lens cover) of a video camera which permitted imaging an area about 350 micrometers in diameter. The 181 x 256 detector focal plane array permitted resolution of features on the order of a few microns in diameter. Over 30,000 frames of video data were recorded, and selected frames were digitized using a Data Translation digitizer.

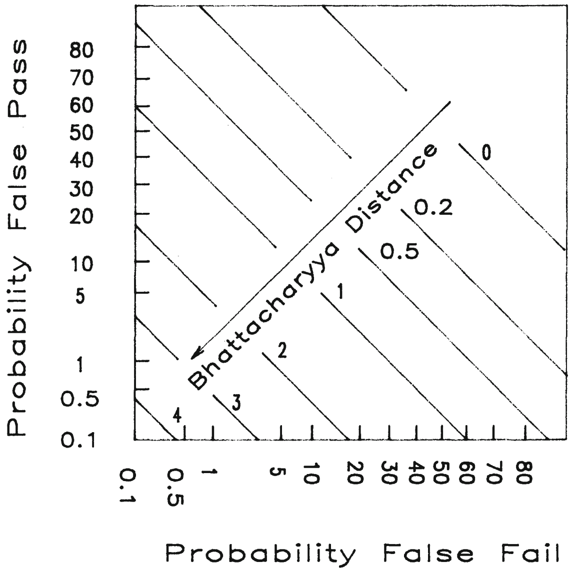

Fig. 1. Relation of false-pass and false-fail errors for Gaussian statistics and equal covariance matrices as a function of Bhattacharyya distance.

This data base afforded much larger sample sizes for the KENN code statistical pattern recognition package than did the scattering envelope data, which is discussed below in greater detail. The scattering data approach may hold more promise for 100% inspection on the production line, because samples are obtained from a much larger field of view. Thus an automated installation--unlike the laboratory equipment--would permit rapidly gathering a large number of samples. Also, from a preliminary look, the scattering data seems to show more promise in making defects more readily apparent.

Nevertheless, insufficient scattering data has been obtained to apply the KENN code, whereas sufficient video data was available. The digitized data was divided into six 20 x 20 windows of 400 pixels. Histograms for the gray scale intensity (normalized to the intensity of the brightest pixel in the window) were formed in four domains, 0-20%, 20-40%, 40-60%, 60-80%. The cummulative sums (0-20%, 0-40%, 0-60%, and 0-80%) were the four elements of the feature vector for each window.

By manipulating this rather simple set of features, it was possible to obtain a PFF/PFP characteristic roughly (since the data did not have a Gaussian distribution) comparable to a Bhattacharyya coefficient of 1.3 in Figure 1. Though far from what would be required for the performance of a classifier in industry, this result does illustrate the application of the discrimination technology to quality control.

It is also not clear how much the result might be improved with the aid of the broad range of image processing techniques available. But for the reasons cited above, the primary effort is now being directed to enlarging the scattering data base rather than to improving performance of the video data classifier.

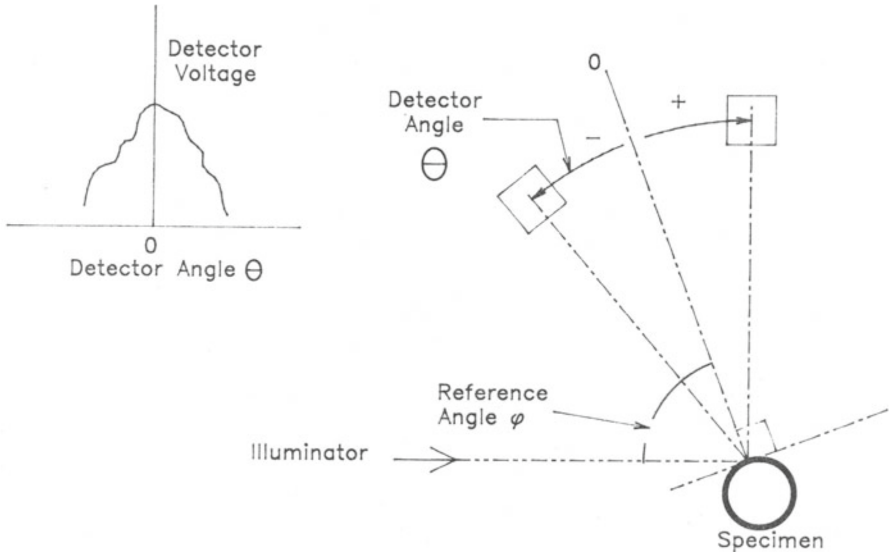

Fig. 2. Schematic of scattering measurement configuration.

OPTICAL SCATTERING DATA

The scattering envelope is a simple signature formed by measuring the light intensity scattered from an object's surface as a function of aspect angle to the surface normal. Figure 2 illustrates the configuration used in this study. Illumination was provided by a Spectra Physics 15 mw Model 120s HE-Ne Stablite Laser and Power Supply. The #SD-444-42-R-261 silicon photovoltaic detector was supplied by Silicon Detector Corporation. Detector voltage was used as a measure of relative intensity of the scattered light since there was no need for an absolute calibration. The field of view of the detector covers to bulk of the illuminated surface [5].

By varying the angle of the detector, the image of the specimen is swept across the detector positions. If each detector position were replaced by an actual detector, angular motion of the specimen would generate scattering intensity amplitude data varying with the angle between the illuminator and the specimen. One can imagine that by combining motions of illuminator and specimen the configuration of Fig. 2 could be readily implemented in a production environment.

Scattering data was taken from specimens with scratches, scuffs and inclusions characterized by micrography with a Nomarski DIC microscope [5]. Data from one of these a large surface inclusions flaw about 150 micrometers in diameter, is discussed below. The specimen was received from its donor, the NORTON Company, with a circle scribed around the inclusion which was visible in the scattering envelopes and was useful as a reference point. The raw scattering envelope data for three illuminator orientations is shown in Figure 3.

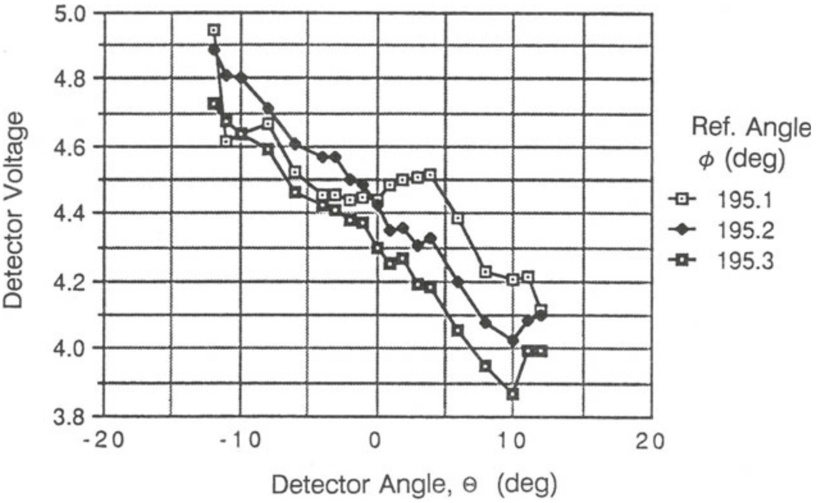

Fig. 3. Raw envelope data for large inclusion.

Evidence of the scribed mark appears fairly clearly at the lower right, but the inclusion is only faintly apparent. Averaging the data in the three envelopes of Fig. 3 (not shown) does not make evidence of the inclusion more prominent. But in Fig. 4, the "detrended" data, the inclusion becomes more evident with a characteristic behavior or an oscillation from dark to light and back to dark again.

The detrending process used in Fig. 4 is based on a simple curve fit representing the results of scattering theory in removing the bias from the scattering envelope caused by the sloping curved surface of the ball bearing. Scattering theory to remove known artifacts from the background is a critical, tool in processing optical data for QC applications. The "Defense Laser Target Signature (DELTAS) Code" makes this tool readily applicable for practical computations in a wide range of circumstances [6].

Figure 5 shows a Fast Fourier Transform (FFT) of the data in Figure 4. An FFT of data from an unflawed surface is shown in Fig. 6 for comparison. The flat behavior of the benign background is apparent and the difference between the behavior shown in Figures 3 and 4 could be readily identified and used in an automated system. The spike at the left of Fig. 5 is an artifact of the background caused by the specular glint of the illuminator. With the aid of scattering theory (e.g. [6]), an algorithm can be written to remove this source of background noise.

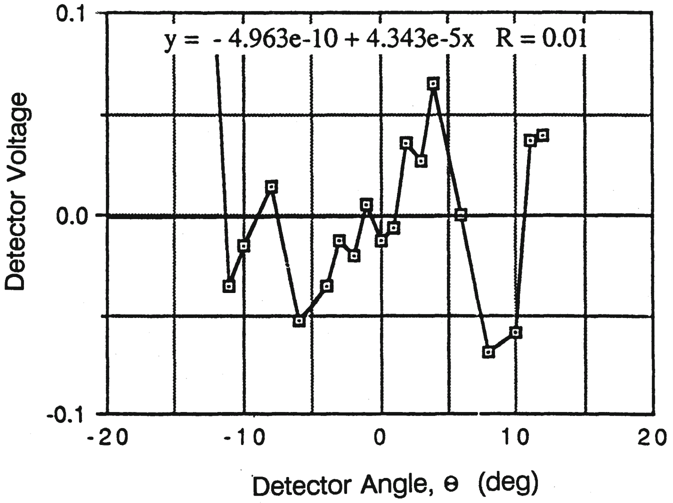

Fig. 4. Detrended averaged data for large inclusion.

CONCLUSION

Results presented herein represent the accomplishment of approximately a 6 man-month level of effort SBIR study. Inevitably a significant part of the effort has gone to the familiarization process involved in transferring skills developed in another field to the QNDE environment. As anticipated at the outset, it was not possible to collect and qualify a set of data complete enough to warrant a

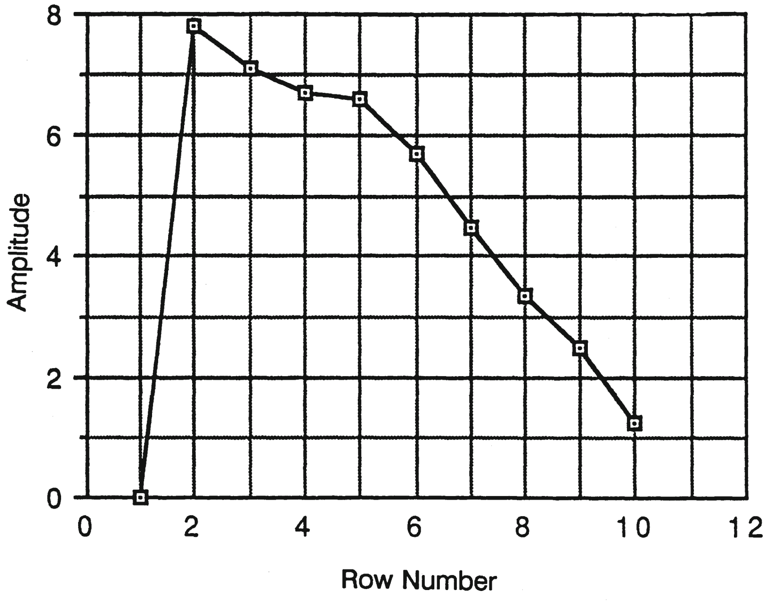

Fig. 5. FFT of detrended inclusion data.

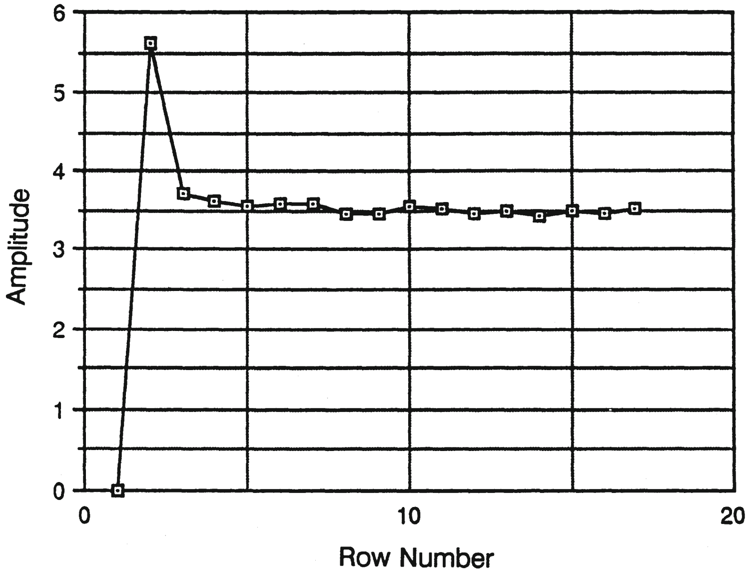

Fig. 6. FFT of typical unflawed background.

conclusion about the viability of the approach. Only limited and heuristic experimental and calculated results were obtained.

These results provide encouragement to proceed further, and the way to proceed has become clearer. The first priority is to augment the experimental scattering envelope data, supplemented by modeling to remove the background artifacts. Application of the statistical techniques of the KENN code scattering envelope data is the next step.

ACKNOWLEDGEMENT

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