TOMOGRAPHIC APPROACHES TO NONWOVENS STRUCTURE DEFINITION

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RELEVANCE TO NTC MISSION AND GOALS:

The thrust of the tomographic approaches project is to better understand the structure of thick, three-dimensional nonwoven structures, many of which have high-performance applications. Better understanding of the structure will lead to improvements in products, product performance, and in the technologies for manufacturing these products. In order to facilitate this project, we have obtained the participation of personnel and facilities at The Center for *In Vivo* Microscopy at Duke University Medical Center (DUMC) (MRI) and at Oak Ridge National Laboratories (ORNL) (micro X-ray tomography). By involving personnel and facilities at these laboratories, which generally have not been involved in textile-related projects, we are pursuing a unique, collaborative effort. We will also be taking advantage of highly sophisticated imaging facilities not yet available on the NCSU campus. In a development which will make this technology available to academic and industrial researchers, NCSU is expected to build a synchrotron ("STAR") on the Centennial Campus sometime in the next five years. We have been told that micro X-ray tomography images will be available from this facility at a cost of around $200/specimen. We expect this technology to be useful in the analysis of conventional textile structures as well as nonwovens.

GOALS:

The goal of this project is a technology which permits the visualization and quantification of the three dimensional structure of a thick nonwoven fabric of arbitrary density based on tomography. The technology will combine methods for obtaining experimental tomographic data having adequate resolution with methods for analyzing the data to give the desired statistical structural parameters. The results desired are 1) the ability to visualize the structure via tomographic "slices," and 2) the three-dimensional orientation distribution function for the fibers and a characterization of the internal void space.

DETAILS:

While the technology for obtaining and reconstructing tomographic data on macroscopic specimens, e.g. human organs, is highly developed (CT scans, MRI), for the most part evaluation of these data relies only on qualitative subjective observation by a specially trained radiologist. While there is a large literature on quantitative two-dimensional image analysis of fibrous structures, there is little for three-dimensions.

The experimental techniques available to us are serial sectioning (very time-consuming for high z-direction resolution), confocal microscopy, and tomography. In general, the methods for

obtaining the data provide relatively low resolution compared with the size of a single fiber in a nonwoven, or require considerable time and manpower. Based on a literature survey, it was decided to evaluate magnetic resonance imaging (MRI) and micro x-ray tomography for obtaining the raw tomographic data. Also based on the literature survey, it was decided to initially base analysis methods on extending the two-dimensional morphological image analysis methods to three-dimensions. These methods are being developed within the commercial software "Applications Visualization System" (AVS).

A DEC workstation with 24 megabytes of memory was purchased for the project and is dedicated to software development and image analysis. Following our development of the sample preparation technique, Dr. Alan Johnson of the Center for In *Vivo* Microscopy at Duke University Medical Center has provided us with a data file containing the tomographic image of a paper-maker's felt. We have learned to manipulate these data so the image can be viewed using NIH imaging software on a MacIntosh computer, although, due to the size of the file, memory constraints have caused problems.

The initial specimen to be analyzed is a needlepunched papermaker's felt provided by Weavexx Corporation. Papermaker's felts are dense, strong, and durable felts made by needlepunching a needle felt into a woven monofilament scrim. The monofilament scrim provides the dimensional stability needed in paper machine applications. For our purposes, the monofilament, which has a much larger denier than the needled fibers, provides a landmark for use in visualization.

Theoretical analysis and the development of algorithms and software are the keys to success of this work. Applying and demonstrating the Hilliard/Komori-Makishima theory in order to quantify the ODF is the immediate goal now that tomographic data is available.

The problem of resolution is being addressed. The 3 denier fibers in this felt have a diameter of approximately 15 microns. The MRI resolution is 20 microns. Therefore, special algorithms are being developed to identify a fiber (separate from noise), and to provide its location.

Theoretical Background:

According to the Hilliard/Komori-Makishima (HKM) theory, the three-dimensional orientation distribution function (ODF) of a fibrous structure can be obtained by solving the integral equation:

$$\nu(\Theta,\Phi) = L\iint d\phi d\theta\, A(\phi,\theta;\Phi,\Theta)\, \Omega(\phi,\theta) \sin\theta \qquad (1)$$

where $\nu(\Theta,\Phi) \equiv$ fiber intersections per unit area on plane with normal $[\Theta,\Phi]$

L = total length of fiber in a unit volume

$= 1/\pi \iint \nu(\Theta,\Phi)\sin\Theta d\Theta d\Phi$

$$A(\phi,\theta;\Phi,\Theta) = |\sin\theta \sin\Theta \cos(\phi - \Phi) + \cos\theta \cos\Theta| \qquad (2)$$

$\Omega(\theta,\phi) \equiv$ *jiber orientation distribution function* in spherical coordinates

The normalization condition is $\iint \Omega(\theta,\phi)\sin\theta d\theta d\phi = 1$.

$\Omega(\theta,\phi)\sin\theta$ is the function we desire from the experimental data. An estimate of $\Omega(\theta,\phi)\sin\theta$ is obtained by counting the number of fiber intersections in a large number of unit area planes, then numerically solving (1). This part of the project has been completed.

Implementation:

To analyze the raw tomographic data, the following steps are required:

1. Process the data to remove noise.
2. Count the intersections of fibers with secant unit area planes with various normals $[\Theta,\Phi]$.
3. Solve the HKM equation for Ω using a two-dimensional Fourier series approximation.
4. Implement a least squares method to solve for Fourier coefficients up to fifth order.

These steps have been implemented and the procedure and algorithms confirmed on a number of simple computer-generated model structures. A road block was encountered when we found that the method involves inverting a matrix which is nearly singular. However, this was overcome with standard singular value decomposition (SVD) numerical methods.

Analysis of Model Structures:

Four model structures were developed using straight fibers:

Model I: all fibers parallel to the Y-axis
Model II: all fibers parallel to the X-axis
Model III: all fibers parallel to the Z-axis
Model IV: equal numbers of fibers parallel to the X- and Y-axes

The number of intersections were counted for ten sets each of unit secant planes at 10 degree increments of Θ and Φ. Equation (1) was solved numerically for $\Omega(\theta,\phi)\sin\theta$. Figure 1 shows the results for the number of intersections for Model I, while Figure 2 shows the ODF for Model I. We investigated third to fifth order Fourier solutions to Equation (1). The number of terms requiring calculation increases rapidly as the order increases: 48 terms for 3rd order, 80 for 4th, 120 for 5th, etc.

The results seen in the four models are intuitively correct. If it were possible to use a larger number of terms, the peak shown in Figure 2 would more closely approximate a delta function – a closer approximation of the ODF for a bundle of straight parallel fibers. Since ODF's in nonwovens are never delta functions, we are confident that a solution higher than fifth order will never be needed.

Analysis of Real Fabrics:

Using tomographic data provided by DUMC, the procedure has been applied to a real fabric. Tomographic "slices" of this fabric are shown in Figure 3. A preliminary predicted ODF based on 5th order Fourier analysis is shown in Figure 4.

WHAT HAS BEEN ACCOMPLISHED:

The theoretical analysis has been developed using advanced computation techniques, and has been demonstrated for four simulations of known fiber orientation. The ODF response surface for these four simulations appear to be correct. Techniques have been developed and implemented to process the raw MRI image data: file handling, noise reduction, and filtering. Techniques to identify individual fibers in the image data have been developed.

Sample preparation techniques have been developed, and MRI tomographic imaging data have been generated at Duke University Medical Center on a dense three-dimensional needle felt. Micro X-ray tomographic images have been generated at ORNL but the results have not been forwarded to us yet.

The MRI image data has been processed, and transformed for viewing and manipulation. The data have been analyzed and an ODF response surface generated.

Image resolution continues to be our main concern. If imaging with micro X-ray tomography is successful, resolution potential could be improved from the current 20 microns for MRI to 3 microns.

PLANS:

Process the higher resolution micro X-ray tomography data generated at ORNL using the paper maker's felt to determine the applicability of this imaging technology: view the image, choose a portion of it for analysis, and determine the three-dimensional ODF.

Verify the analysis by making a model structure of known ODF (thick layered cardweb) and determining the ODF using MRI and micro X-ray tomography. Verify using a thick woven fabric.

Work with ORNL to optimize the electron density contrast to achieve best tomographic images of thick nonwoven fabrics using micro X-ray tomography.

Begin developing systems for analyzing internal pore structure from tomographic data.

Select additional thick structures of interest to the industry, and apply and refine the technique on those structures.

Publish a paper descriptive of work to date.

RESOURCE MANAGEMENT:

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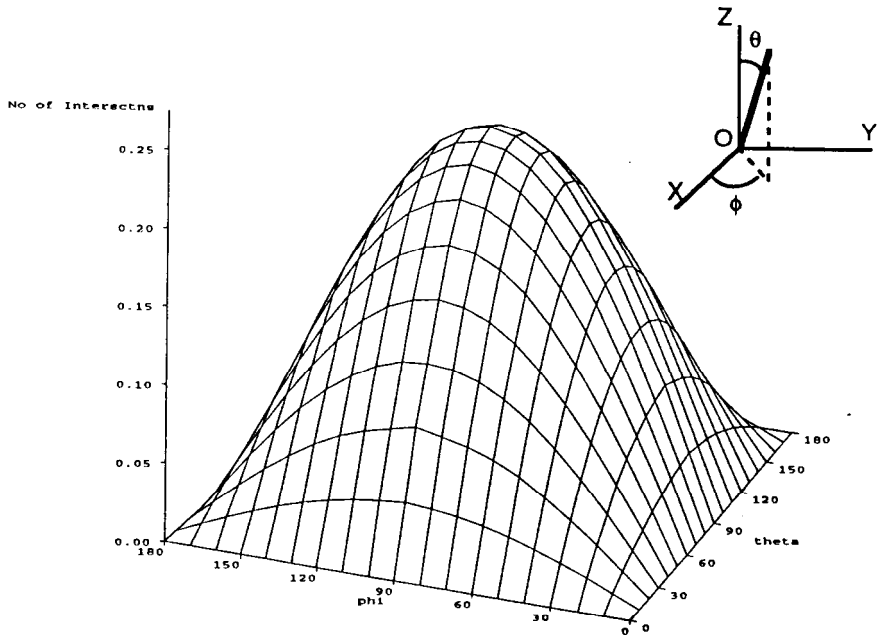
Figure 1: Number of Intersections of Model I



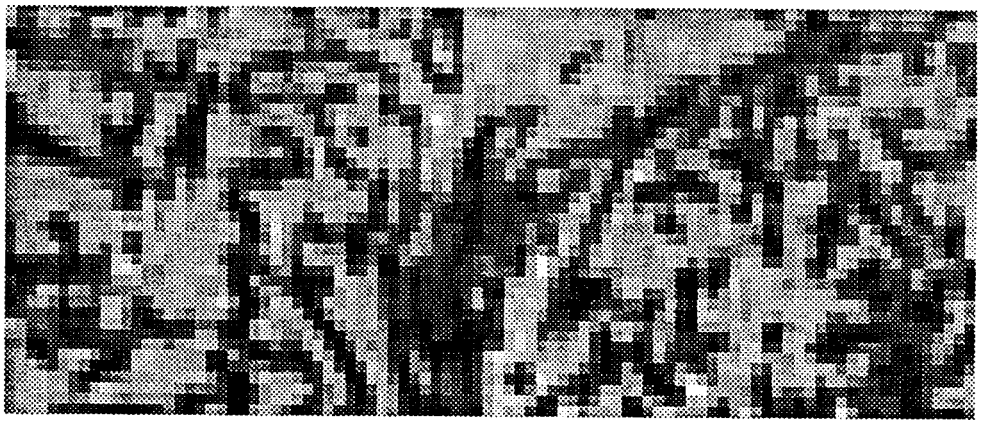


Figure 3. Tomographic "slice" through a vertical plane of a papermaker's felt. The reorientation of fibers due to a needle penetration can be seen in the center of the image.

Figure 2: Orientation Distribution Function of Model I

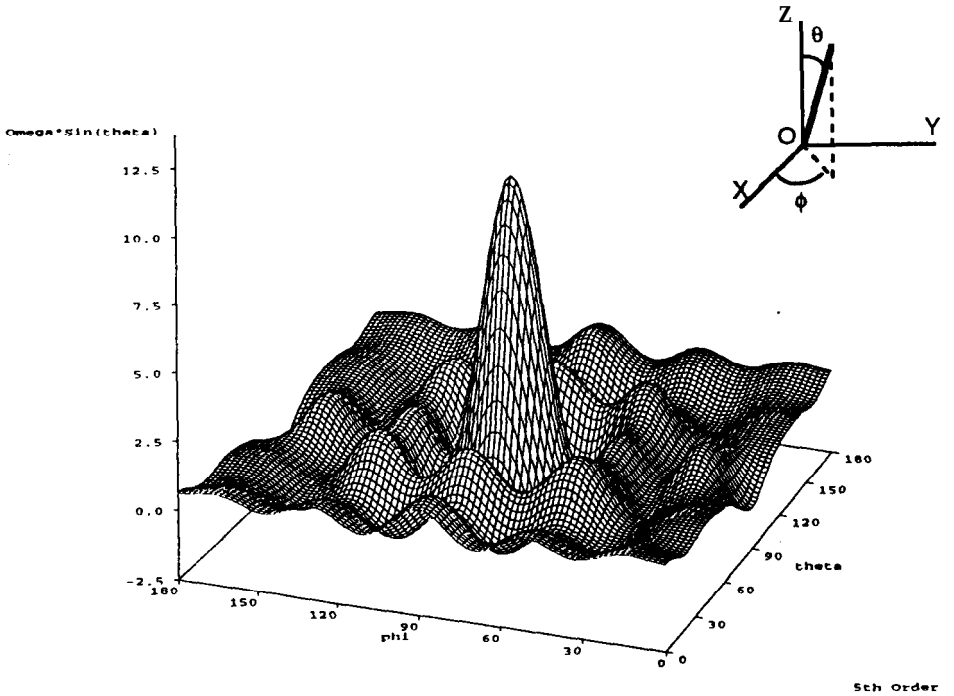


Figure 4: Orientation Distribution Function of Real Fabric