A PRECISION TECHNIQUE FOR MOUNTING SCINTILLATING FIBER RIBBONS ON A CYLINDER FOR CHARGED PARTICLE TRACKING

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ABSTRACT

A technique for accurately mounting scintillating fiber ribbons on a cylindrical support structure has been developed for the construction of large fiber tracking detectors. This method utilizes a "ribbon laying machine" to accurately position the ribbons while they are being mounted. A large Coordinate Measuring Machine (CMM) is used to control the process by verifying the alignment at each step. Using a prototype ribbon laying machine, 2 m long test ribbons have been placed on a cylinder 1/2 m in diameter, in axial and 2° stereo orientations. The placement accuracy in $R\delta\phi$ achieved for both cases was $\sim 30\mu$m for deviations from axial or helical alignment at all points along the length of the ribbon, and $\sim 30\mu$m for the relative spacing between adjacent ribbons. By including two calibration constants for each ribbon, determined from CMM measurements, the overall fiber positions can be known to $\sigma_{R\phi} \sim 20\mu$m. Properties of a lightweight cylinder prototype are also investigated.

1. Ribbon Mounting for Fiber Tracker Construction

In future collider experiments, such as DØ and SDC, where the advantages of low occupancy rates and fast response times make scintillating fibers an excellent choice for a tracker design, one is confronted with the problem of how to position fibers accurately for good spatial resolution. Fiber positioning is complicated by the fact that the fibers cannot be significantly stressed without being damaged. A very large number of readout channels must be accommodated in a tracking system ($\sim$ 80,000 for DØ), and many degrees of freedom must be removed when precisely fixing each fiber's location. Furthermore, the fibers must be held rigidly by some means of external support along their entire length. This support must be lightweight so that the amount of structural material found inside the tracking volume is minimized.

Purdue University has been working with FEPCO Coordinate Measuring Services of Noblesville, Indiana, to develop a construction method whereby precise fiber ribbons can be mounted on a lightweight, precision cylinder, in answer to the fiber positioning question. The modularity of ribbons allows us to handle many channels at one time and reduce the number of degrees of freedom to just a few per ribbon. Tracker construction can thereby be completed in a reasonable amount

of time. Ribbons have been fabricated with up to 255 channels in a doublet layer structure, and with fibers spaced precisely to better than 20μm in both layers, as a demonstration of the viability of this technique[2]. For ribbon support, a precision cylinder formed from a carbon fiber composite was selected because it comes closest to the ideal coordinate system required by most collider experiments. It has an excellent strength to mass ratio while maximizing detector acceptance and measuring accuracy over a large tracking volume. The method described below for mounting ribbons to cylinders will be used to construct a scintillating fiber tracker for the upgraded DØ experiment.

2. Goals for Placement Accuracy

Accuracy requirements for fiber placement are driven by the need for good spatial resolution for charged particle tracking without excessive calibration. One would like to know the position of each fiber precisely so that the limiting factor in resolving hit points is just the finite size of the fibers rather than their deviation from an expected location. In the limiting case, the resolution for a doublet structure with each layer offset precisely by 1/2 the fiber spacing D can be calculated from simple geometrical considerations to be

$$\sigma_{R\phi}^{\text{doublet}} \approx \frac{D}{2\sqrt{12}}.$$

For example, using fibers of 850μm diameter (a typical size for a tracking experiment), spaced with a negligible gap, we could achieve

$$\sigma_{R\phi}^{\text{doublet}} \approx 125\mu\text{m}.$$

If we make a superlayer where two doublets are offset by exactly 1/4 the fiber spacing, the resolution is improved by a factor of 2 to ~60μm. To achieve the best possible resolution, then, the ribbons must be placed with a positional uncertainty that is less than this. Precise fiber positioning in R is not as critical as it is in $R\phi$ if our main interest is in obtaining good momentum resolution for tracks coming from an interaction point. The dominating requirement can be shown to be σ_R ~150μm, arising from the requirement that errors in R will accumulate over the width of the ribbon in $R\phi$ when the number of channels in the ribbon is large[1]. The goals for placement accuracy are then summarized as follows:

$$\sigma_{R\phi}^{\text{placement}} \leq 50\mu\text{m}$$
$$\sigma_{R}^{\text{placement}} \leq 150\mu\text{m}.$$

In principle, one could imagine calibrating every fiber in a large tracker for its alignment at all points along the length of the fiber to reach these goals. In practice, however, this is impossible because of the number of calibration parameters and analysis time it would require. By positioning ribbons accurately, the number of

calibration parameters can be reduced to just a few per ribbon and the best possible resolution can be accomplished with simplicity.

3. Use of a Coordinate Measuring Machine

This technique for mounting ribbons precisely has proven successful because a high level of quality control is achievable using a large-volume Coordinate Measuring Machine (CMM). We use the CMM to provide a continual feedback of information that insures precise mechanical alignment throughout the entire mounting operation. Mistakes are eliminated and tracker construction is speeded. The accuracy with which many individual measurements can be repeated is enhanced by on-line computer software for numerical control. The CMM is not just used to verify ribbon position after placement. Among the tasks performed are the following:

- Precise inspection and characterization of ribbons and cylinders prior to ribbon mounting.
- Control over ribbon placement and verification of mechanical alignment during all steps of ribbon mounting.
- Immediate verification of a ribbon's position afterward by sampling fibers in the ribbon.
- Immediate calibration of the detector for actual fiber locations. For a large detector, achieving a spatial calibration prior to installing it in an experimental setup can be a significant advantage for early analysis of data taken.

We have chosen to use a large bridge-type CMM available at FEPCO Coordinate Measuring Services for these tests. With an absolute measuring accuracy of 0.0005 inch bandwidth (per B89 standard) over a volume of 3251 mm × 1829 mm × 1372 mm, this machine is capable of accommodating even the largest DØ cylinder. Fibers can be located with the CMM by iterating multiple touches locally using a small pencil probe. The typical repeatability for these measurements has been shown to be ~1.5μm[2].

4. Cylindrical Support

A lightweight but rigid design for a cylinder to which ribbons can be mounted has been achieved with the cross sectional structure shown in figure 1. It is constructed from a honeycomb paper core sandwiched between two thin veneers (0.0077 mil-thick) of carbon fiber and epoxy resin. This composite structure results in an effective mass of only 0.5% radiation lengths at 90° to the beam line. The variation of both inner and outer surfaces from true cylindricity has been measured to be $\sigma_R \leq 100\mu$m for points over the entire surface and at $\sigma_R \leq 20\mu$m locally. This surface precision will allow ribbons of up to several hundred channels to be placed on it without compromising the spatial resolution[1].

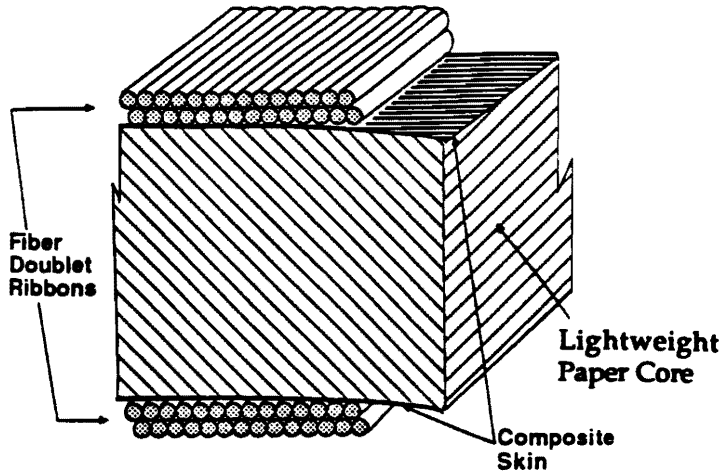

Figure 1: Cross sectional view of a composite structure for cylindrical ribbon support, whose effective mass is only 0.5% radiation lengths at 90° to its axis. Ribbons can be mounted on both the inner and outer surfaces.

Figures 2 and 3 compare the deflection of the cylinder when a uniform load of 50 lbs is placed along the top. Two cases were considered (1) where the ends are unconstrained by any rigid attachment and (2) where the ends are constrained to a circular shape by fixing them to circular aluminum plates. The 50 lb load exceeds that of a superlayer of four doublets completely covering the cylinder. All points on the cylinder show minimal deflection, especially in the constrained case where $|\delta R| < 100\mu$m.

Since moisture absorption by the carbon fiber can also lead to changes in the cylinder shape, we compared two independent maps of the cylinder's surface taken during periods of high and low humidity respectively. We observed average radii of

$$R_{fit} = 272.173 \pm 0.010 \text{ mm at } \geq 70\% \text{ relative humidity}$$
$$R_{fit} = 272.125 \pm 0.010 \text{ mm at } \sim 20\% \text{ relative humidity,}$$

indicating roughly a $3\times10^{-3}\%$ change in radius per 10% change in relative humidity. Changes in the cylinder length were observed to be less than half that of the radius. Local variations in the surface indicating a deviation from cylindricity at either high or low humidity were not observed.

5. Prototype Ribbon Laying Machine

The ribbon mounting process is facilitated mechanically by a ribbon laying machine, shown in figure 4. The cylinder is attached via end plates fixed to a steel shaft. This shaft is supported at both ends by bearings mounted to a rigid steel framework. Brakes can be applied at both ends of the shaft to fix the cylinder in a given angular rotation. Above the cylinder, a precision jig plate mounted on

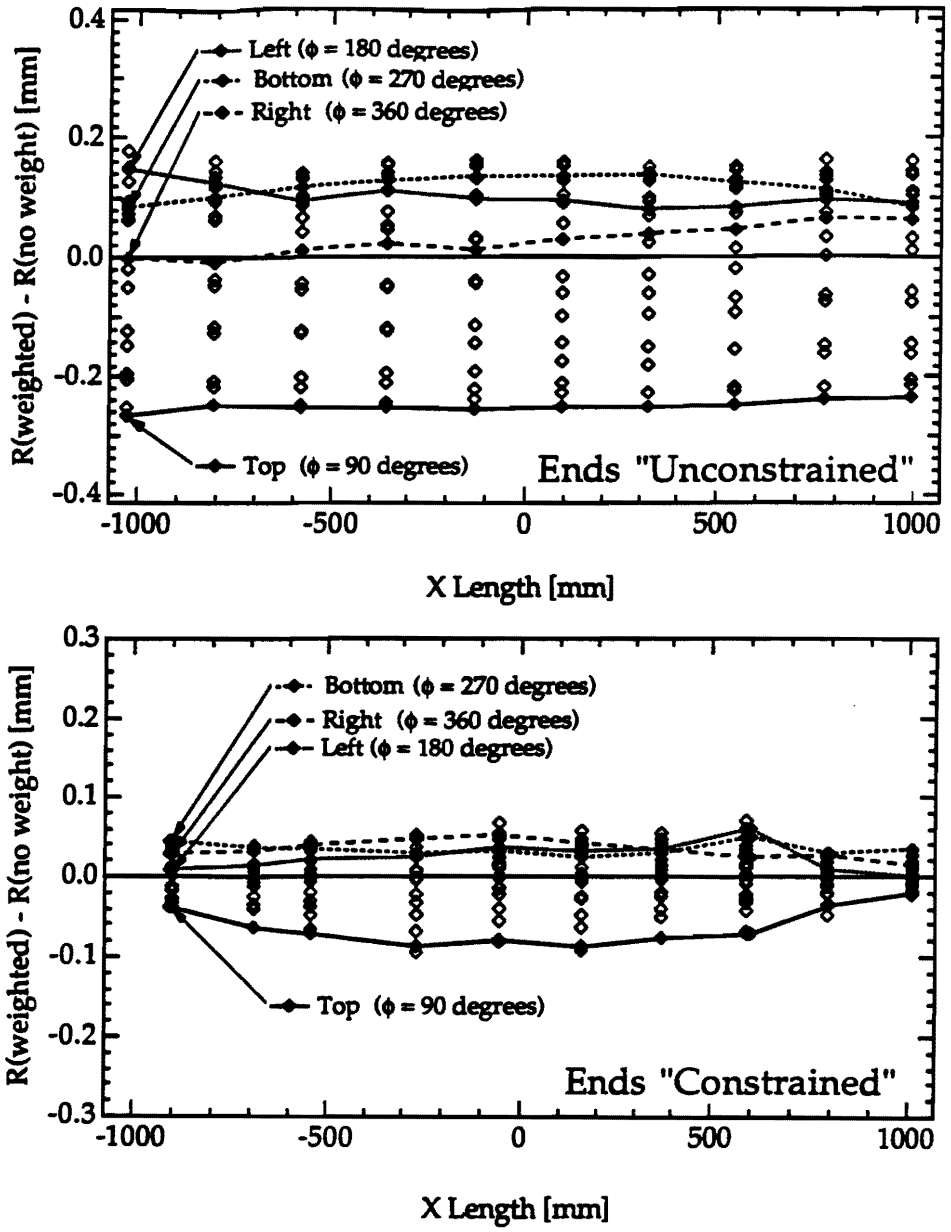

Figure 2: Shape variation in the cylinder as a function of length, under a 50 lb weight applied uniformly along the top.

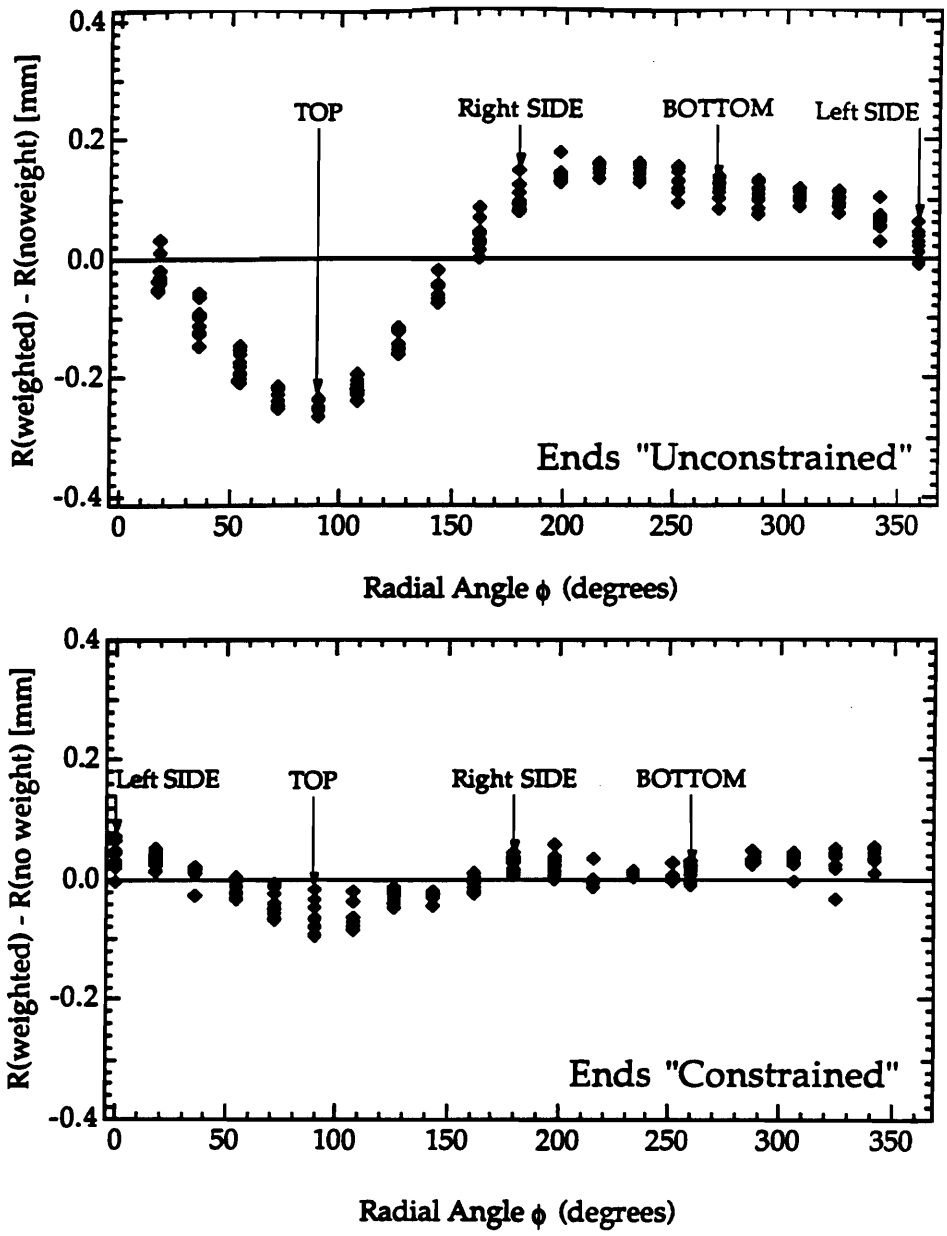

Figure 3: Shape variation in the cylinder as a function of azimuthal angle, under a 50 lb weight applied uniformly along the top.

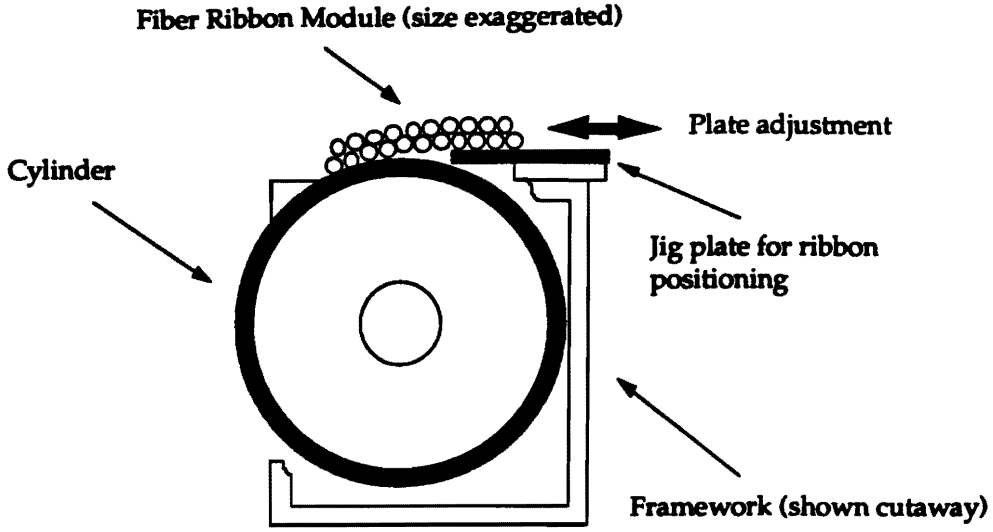

Figure 4: Features of the prototype ribbon laying machine. Micrometer head adjustments are used to position both ends of the plate in precise alignment above the cylinder.

linear track sliders is used to hold the ribbon while mounting it. This jig plate was machined from 1/4 inch plate stock of 7075 aluminum alloy, in a highly accurate manner similar to the jig plates used for ribbon production[2]. V-shaped grooves for positioning the fibers are cut along the length of the plate at precise intervals to match the fiber pitch. We compensated for the distortion induced in the plate as it was bolted to supports on the machine by adding shim stock under and behind the plate. A straightness of better than 20μm was achieved over the full 2 m length of the plate by checking down grooves with the CMM.

The linear track sliders to which the plate is attached allow the plate's position to be adjusted horizontally with respect to the cylinder. Micrometer head adjustments and clamps are used to precisely position each end of the plate in an aligned location determined by the CMM.

6. Ribbon Mounting Procedure

To establish a baseline cylindrical coordinate system for our test, we mapped the cylinder's entire surface under the CMM prior to mounting any ribbons. This map was then referenced to tooling balls mounted on the cylinder. Alignment of the ribbons and the cylinder could then be verified at any time during subsequent steps simply by locating the tooling balls and jig plate with the CMM.

The ribbon mounting procedure is as follows:

1. The cylinder is rotated into an approximate position and the brakes at the ends of the shaft are applied. The cylinder's exact location is then determined

by measuring the tooling balls with the CMM.

2. After applying a layer of transfer adhesive to the surface of the cylinder, and removing its paper backing (we used 0.002~0.005 mil-thick adhesive manufactured by 3M Corporation in these tests), the jig plate is guided into alignment by adjusting the micrometer heads. With the aid of the CMM, end-to-end alignment of ~10μm can be regularly achieved.

3. A ribbon is then placed in the jig so that roughly two thirds of its width extends off the plate over the cylinder and only one third is held by the grooves. Small free weights are gently applied to keep the fibers in the jig.

4. The part of the ribbon extending over the cylinder is then allowed to "hinge down" slowly into contact with the cylinder, so that the leading edge fibers (30 or so) touch, defining the ribbon's placement.

5. When a bond at the edge of the ribbon has been achieved, the weights are removed and the trailing edge of the ribbon is carefully lifted out of the plate. The plate is retracted, and the remainder of the ribbon is thereafter allowed to come into full contact with the cylinder.

Since some handling of the ribbon is involved, there is the danger of disturbing a ribbon's alignment. We found that after some practice this could be controlled by taking care that lateral stresses were not applied when touching the ribbon.

7. Placement Accuracy

Our placement accuracy improved with each succeeding ribbon as we learned to identify mechanical and procedural improvements during the test. For example, we noticed after a few ribbons that typically small variations in the fiber pitch (~1μm per fiber spacing) from ribbon to ribbon can occur, due to handling the ribbons and also due to the moisture absorption or drying properties of the glue mix used in their construction. Although minuscule, these variations will add up to a macroscopic placement error when collected over a sizable ribbon width (50 fibers or more). We found we could control these pitch variations to an acceptably small level by keeping ribbons in the same production jig until just prior to mounting them.

The placement accuracies achieved for ribbons mounted in both axial and stereo configurations (calibrated for fiber pitch only) are plotted in figures 5 and 6. In both cases, the offset from the target position in $R\delta\phi$ is small, ~30μm, and the deviation from alignment along the entire 2 m length is also ~30μm. By calibrating each ribbon for the offset and slope, represented by the fit lines in figures 5 and 6, the fiber position can be known to $\sigma_{R\phi}$ = 20μm. This is essentially the intrinsic accuracy of the fiber alignment within the ribbons themselves. Deviations of the fiber positioning in R were also measured to be consistent with the fluctuations in the cylinder surface's shape (σ_R <100μm), even when multiple layers of doublets were build up into a superlayer.

In conclusion, CMM control results in a precision method for ribbon placement. CMM measurements provide us with a powerful means by which we can make an immediate calibration for fiber alignment prior to installing a tracker in an experimental setup. Because of the accuracy in ribbon construction and placement, only a few calibration constants per multi-channel ribbon are needed to reach the best possible spatial resolution in a large fiber tracking system.

6. References

1. D. Koltick, "Accuracy Requirements for the Construction of the D-Zero Scintillating Fiber Charged Particle Tracker," DØ note #2010, March 5, 1992.
2. J. C. Cooper, "Construction and Mechanical Qualification of Scintillating Fiber Doublet Ribbons," presented at this workshop.

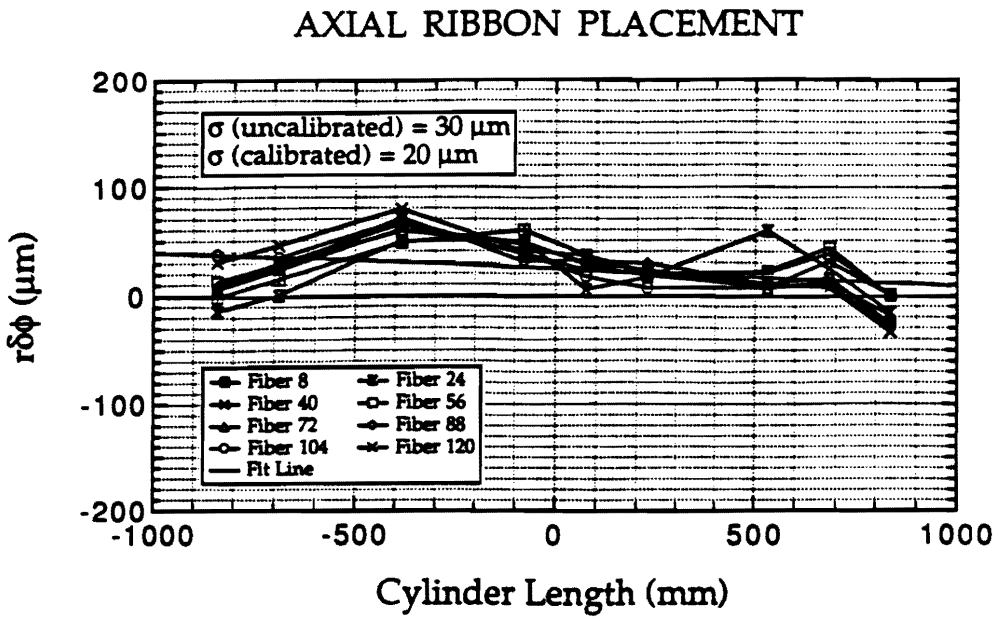

Figure 5: Measured deviations of fiber positions from a target location in $R\phi$, for a ribbon mounted parallel to the cylinder's axis.

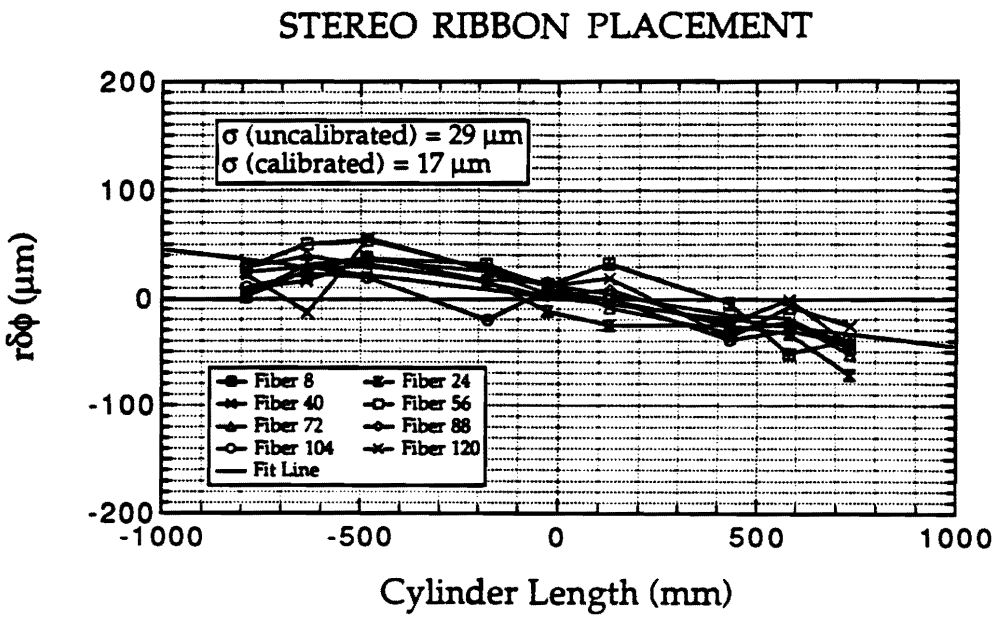

Figure 6: Measured deviations of fiber positions from a target location in $R\phi$, for a ribbon mounted at 2° stereo angle from the cylinder's axis.