An investigation of the sampling bias of the beard method as used in HVI\textsuperscript{TM}

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The beard method is used for sampling cotton fibers to generate fibrograms from which length parameters can be obtained. It is the sampling method used by the Uster High Volume Instrument (HVI\textsuperscript{TM}). A fundamental issue of this sampling method is its bias since the mathematical computation to obtain length parameters is quite different. There have been different assumptions regarding the bias of the beard sampling method. In our experiments, we have seen discrepancies in measurements that cannot be explained as length-biased or unbiased, especially in the short fiber region. We report a fundamental research, including experimental and theoretical analysis, and computer simulations, that reveals the bias due to this sampling method. We find that the beard sampling method as used in HVI is not completely length-biased; fibers sampled by using this method are similar to the original fibers except in the short fiber region. Short fiber content (SFC) of the sampled fiber is lower than that of the original fiber, and this difference is inherently introduced by the sampling method.

**Keywords:** cotton; HVI; beard method; fiber length measurement; sampling bias; short fiber content

**Introduction**

The beard method was developed to test cotton fiber length parameters rapidly. Cotton fibers are selected by the needles of the fiber comb and formed into a gradually tapered fiber beard. Then a measurement device utilizes optical or pneumatic method to scan the fiber beard to generate length fibrograms by measuring the light attenuation or airflow rate along the tapered beard. Various length parameters can be obtained from the fibrogram. Woo (1967) provided a comprehensive appraisal and developed a series of equations for computing different fiber length parameters from fibrograms. Beard method is used by Uster HVI for length measurement. HVI has brought significant impacts on cotton industry (Suh & Sasser, 1996). Because of its speed and consistency, HVI is now extensively used to measure cotton properties, including fiber length parameters and strength, color, trash, and Micronaire (an indicator of cotton maturity and fineness). HVI uses a fiber comb to pick up fibers from the Fibrosampler\textsuperscript{TM} to form a tapered beard. During the sampling process, the fiber comb makes circular movements around the Fibrosampler cylinder in which cotton fibers are held; needles of the comb pick up fibers protruding through the holes on the Fibrosampler cylinder surface. Figure 1(a) and (b) show the comb as used in Uster HVI 900 model and the fiber beard formed by using such a comb, respectively.

![Figure 1. (a) Fiber comb used in the Uster HVI 900 model. (b) Fiber beard formed by using the fiber comb.](image-url)
A fundamental issue regarding this sampling method is its bias, or in other words, if the length distribution of the sampled specimen is the same as that of the original fiber.

There have been different assumptions regarding the bias of the beard sampling method for measuring cotton fiber length. At the very beginning, when Hertel developed the fibrogram theory, he assumed that the probability of a fiber being sampled for fibrogram was proportional to its length; this is the length-biased sampling assumption (Hertel, 1940; Hertel & Zervigon, 1936). Zeidman, Batra, and Sasser (1991a) provided a derivation that used the unit step function to prove that sampling for fibrograph is length biased. This derivation explains the length bias of the original Hertel sliver clamp sampling. On the other hand, Chu and Riley later found that sampling using the HVI Fibrosampler did not agree with the length-biased sampling assumption. The assumption was then revised to that each fiber has equal probability of being sampled (Chu & Riley, 1997).

However, neither the length-biased sampling nor the unbiased sampling can explain some discrepancies in measurements that were observed in experiments, especially in the short fiber region (Cui et al., 2007). Researchers have found that short fibers have important impacts on yarn processing efficiency and quality (Backe, 1986; El-Mogahzy, Broughton, & Guo, 2000; Hequet, 1999). In addition, there have been various researches on the measurement of short fibers (Bargeron & Sasser, 1993; Cui, Calamari, Robert, Price, & Watson, 2003; Knowlton, 2001, 2004; Zeidman et al., 1991b).

We conducted this research to verify if the beard sampling method as used in HVI is biased and to explain the reason.

**Experimental observations**

We measured length distributions of eight cottons of different staple lengths by use of the Uster Advanced Fiber Information System (AFIS™). At first, we took samples in tuft size by hand from cotton bales, and then we measured the samples on AFIS to obtain length data. At least 35,000 individual fibers were measured for each cotton on AFIS. Length data of these individual fibers were used to calculate the length parameters and to construct the length distribution of each “original” sample.

Then, we used HVI’s fiber comb to pick fibers from the HVI Fibrosampler, took the sampled specimen fibers off the HVI clamp, and tested on AFIS. Again, at least 35,000 individual fibers were measured by AFIS for each sample. The data were used to construct the length distribution of these “picked specimen” fibers.

![Figure 2](image-url)
The following equation reveals the relationship between the mean length by number \( ML_{nl} \) from length-biased sampling process and mean length by number \( ML_n \) from non-biased sampling process (Cui, Calamari, & Suh, 1998):

\[
ML_{nl} = ML_n + \frac{\text{Var}_n}{ML_n}
\]  

(1)

in which \( \text{Var}_n \) is the length variance. Equation (1) shows that if the sampling process is length-biased, then the resulting mean length by number should be always longer than the original mean length by number. Figure 2 shows the AFIS results of the eight cotton samples, of the mean lengths by number of the original samples, the mean lengths by number of the HVI comb selected fibers (measured on AFIS), and the mean lengths by number of ideal length-biased samples, which were calculated by Equation (1). In Figure 2, it can be seen that the mean lengths by number of the specimens picked by HVI Fibrosampler were almost the same as those of the original fibers. Both of them are far shorter than the mean lengths by number of fibers from a length-biased sampling process. This comparison proves that the HVI beard sampling process is not completely length biased.

**Analysis of the sampling mechanism**

In an unbiased sample, the fiber length distribution of the sample is the same as the original fiber population. The characteristics of sampling bias can be obtained by analyzing the probability of a fiber being sampled in the beard sampling method. The following analysis shows that the sampling is completely length biased when there is only one needle (sampling position) in the comb, as shown in Figure 3, or the distance between needles is far larger than the longest fiber in the sample. If the \( i \)th group of fibers has \( N_i \) fibers of length \( L_i \), then the probability of one fiber in this group being sampled is calculated as \( p = L_i/W \), which is the fiber length divided by sampling width \( W \), such as the width of the window of the HVI Fibrosampler. Then the number of fibers in this length group being sampled is given by

\[
n_i = N_i \times L_i / W
\]  

(2)

for \( L_i < W \). This is length biased and it agrees with the result from Zeidman et al.’s derivation based on the unit step function (1991a).

Figure 4 shows the analysis for the situation where there are multiple sampling positions. In this case, the probability of one fiber in the \( i \)th group being sampled is calculated as \( p = L_i/\Delta W \) for \( L_i < \Delta W \), where \( \Delta W \) is the distance between the adjacent sampling positions (needles), and the number of fibers being sampled is still length biased. But once \( L_i > \Delta W \), the probability \( p \) is always 1, which means the fiber can always be picked up thus the sampling is unbiased.

In real situations, fiber orientation is random, which projects more “short” fibers in the direction that is perpendicular to the sampling direction. From the aforementioned analysis we can find that for short fibers, the measurement could be length biased, but for fibers longer than certain length, the measurement is unbiased. The distance between pins/needles of the HVI Fibrosampler’s fiber comb is only about 2 mm. There are more than 30 needles in the HVI fiber comb, in this case the sampling is not completely length biased considering the small distance between needles, but length bias still has its influence in the short fiber region.

**Computer simulations and results**

We simulated the sampling procedure based on our analysis on the HVI fiber comb’s sampling mechanism. At first, in order to validate the change of sampling bias as the distance between needles changes, we simulated the sampling process from an artificial sample of 100,000 individual fibers, in that 50,000 fibers are...
specified as 30-mm long and 50,000 fibers are 15-mm long. The fibers had randomly distributed orientations and positions on a plane. Each fiber’s probability of being sampled was calculated based on the analysis discussed in the previous section.

Figure 5. Simulation that shows the change of sampling ratios between 30-mm fibers and 15-mm fibers with the change of needle distance.

Figure 5 shows the ratio of 30-mm fibers to 15-mm fibers that are sampled. If the sampling process is completely length biased, then the sampling ratio between them should be equal to their length ratio, which is 2, because those two groups have equal

Figure 6. AFIS measured and computer simulated length distributions of staple length 30 fiber.
Figure 7. AFIS measured and computer simulated length distributions of staple length 31 fiber.

Figure 8. AFIS measured and computer simulated length distributions of staple length 33 fiber.
Figure 9. AFIS measured and computer simulated length distributions of staple length 34 fiber.

Figure 10. AFIS measured and computer simulated length distributions of staple length 36 fiber.
number of fibers. If the sampling procedure is unbiased, then the ratio should be 1 because it is not related to length. From Figure 5 we can also see that the sampling ratio is 2 when the distance between needles was larger than 30 mm. This indicates the length-biased sampling situation when the distance between needles is longer than the maximum fiber length. The sampling ratio eventually approaches to 1 as the distance between needles decreases; this indicates that the sampling process is becoming more unbiased if the distance between needles is decreasing. Therefore, the simulation results agreed with our analysis in the previous section. The measured distribution changes from completely length biased to less length biased when the distance between needles decreases.

After the aforementioned simulation, which simulated the sampling ratio of fibers of only two fixed lengths, we then simulated the sampling process to obtain length distributions of fibers picked by the HVI fiber comb. We used AFIS to measure the lengths of original fibers, which were directly selected from cotton bales without using the HVI fiber comb. A special research version of the AFIS software was used so that the data of each measured individual fiber length were saved in the computer. These AFIS measured lengths of the original fibers were used as inputs for generating computer simulated HVI fiber comb specimen lengths. The parameters of the simulations adopted the configurations of a fiber comb of the Uster Fibrosampler 192 used by the HVI 900 model, i.e. 36 needles and 2 mm needle distance.

Although the needles of the fiber comb are short, in reality the sampling process is three dimensional considering that the cotton fibers’ orientations are randomly distributed in a space. Therefore, we developed our simulations based on the assumptions that (1) in fibrosampler’s drum, cotton fibers are randomly distributed with three-dimensional orientations and (2) the holding point by a sampler needle on one fiber is random.

The cotton samples we simulated have nominal staple lengths of 30, 31, 33, 34, 36, 37, and 38. Computer simulated HVI fiber comb specimen length distributions were compared to AFIS measured HVI fiber comb specimen length distributions in Figures 6–12. Each figure has four distribution curves showing the probability density functions (PDF). These four curves are of (1) the original fibers directly from cotton bales (designated “Raw pdf”); (2) the specimen fibers from the HVI fiber comb sampling process (“Sampled pdf”); (3) the fibers from the computer simulated sampling process (“Simulated pdf”); (4) the fibers of the completely length-biased sampling process (“Length-biased pdf”).

Figures 6–12 demonstrate that both computer simulated and AFIS measured length distributions of the
fibers sampled by the HVI fiber comb are far away from the length distributions of the completely length-biased sampling process, instead they are much closer to the distribution curves of the original fibers. Results show that discrepancies between the simulated length distributions and the length distributions of the original fibers are especially obvious in the short fiber region (fiber length < 0.5 inch). In this short fiber region, the curves of the simulated distributions are all lower than the original fibers’ distributions. This means that short fiber contents (SFCs) of the simulated fibers are lower than that of the original fibers (Table 1). But for the region that fiber length is longer than 1 inch, the two distributions almost match each other. These findings agree with the experimental data and support the analysis of HVI fiber comb sampling mechanism discussed in the previous section: the beard sampling method as used in HVI is not completely length biased; fibers sampled by using this method are similar to the original fibers except in the short fiber region. SFC of the sampled fiber is lower than that of the original fiber.

Conclusions
We report in this paper a fundamental research that included experimental and theoretical analysis, and computer simulations to investigate the bias in the sampled fiber length distributions due to the beard sampling method as used in HVI.

Table 1. Computer modeled and experimentally sampled SFCw compared to original fiber SFCw (%).

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>30</th>
<th>31</th>
<th>33</th>
<th>34</th>
<th>36</th>
<th>37</th>
<th>38</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original SFCw</td>
<td>15.24</td>
<td>11.75</td>
<td>10.91</td>
<td>8.21</td>
<td>7.52</td>
<td>7.26</td>
<td>6.40</td>
</tr>
<tr>
<td>Sampled SFCw</td>
<td>12.98</td>
<td>11.49</td>
<td>9.35</td>
<td>7.35</td>
<td>7.12</td>
<td>6.06</td>
<td>5.73</td>
</tr>
<tr>
<td>Difference</td>
<td>−14.87</td>
<td>−2.19</td>
<td>−14.30</td>
<td>−10.47</td>
<td>−0.523</td>
<td>−16.51</td>
<td>−10.47</td>
</tr>
<tr>
<td>Modeled SFCw</td>
<td>13.59</td>
<td>10.37</td>
<td>9.54</td>
<td>7.19</td>
<td>6.53</td>
<td>6.29</td>
<td>5.48</td>
</tr>
<tr>
<td>Difference</td>
<td>−10.88</td>
<td>−11.76</td>
<td>−12.51</td>
<td>−12.33</td>
<td>−13.16</td>
<td>−13.43</td>
<td>−14.25</td>
</tr>
</tbody>
</table>

Note: In this table, original SFCw means SFC by weight of fibers directly measured by AFIS without using the beard sampling method; sampled SFCw means SFC by weight of fibers sampled by the HVI beard sampling method and measured by AFIS; and modeled SFCw means SFC by weight obtained from the computer model that simulates the HVI beard sampling process.
We find that the beard sampling method as used in HVI is not completely length biased; it is nearly an unbiased method, especially for the longer fibers. However, the sampled fibers have an obvious bias in the short fiber region. SFC of the sampled fiber is lower than that of the original fiber. This difference is inherently introduced by the beard sampling method of using needles to select fibers. This research reveals the nature of the bias caused by this sampling method and helps us to understand better how the sampling method affects the length distribution of sampled fibers. This in turn helps to improve the accuracy of SFC measurement by use of the beard test method.

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