Web Density Control Techniques for Nonwoven Air-Laying Processes

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Abstract

This paper describes on-line feedback control techniques for regulating the area density distribution in low-density air-laid nonwoven webs in both the machine direction and the cross-machine direction. The web area density is monitored in real-time by a scanned-laser-based device. The web density distribution along the machine direction is regulated by controlling the transporting belt while the web density distribution in the cross-machine direction is regulated by a vane system in the suction chamber.

1. Introduction

Air-laying is one of the most popular production processes of nonwovens. Air-laid webs are nearly isotropic in terms of fibre orientation. The air-laying process involves three major stages: the opening of fibres using an opening unit similar to a card, the transportation of the fibres to a moving collection screen by airflow, and the formation of the web on the collection screen. Currently, the control of the web density is limited in the machine direction and most of the control methods are adapted from the traditional yarn production processes [1, 2, 3, 4, 5, 6]. However, unlike the linear yarns, nonwoven webs are two-dimensional and therefore the control of the web density must be applied in both the machine and cross-machine directions.

This paper describes feedback control techniques for controlling the web density in the machine direction (MD) and cross machine direction (CD) for nonwoven air-laying processes.

2. The Air-laying Machine

In order to develop the control techniques, an air-laying machine was built based on a conventional roller card with a working width of 560 mm. Fig. 1 shows the layout of the machine. The fiber lap is fed by a pair of feed rollers and is opened by the taker-in. The opened fibers are carded by the cylinder and workers and the carded fibers on the cylinder are then stripped by the airflow and transported into the duct towards the perforated conveyor belt. A centrifugal fan located under the conveyor belt generates the airflow. The fibers are separated from the airflow by the conveyor belt to form a web which is transported away continuously by the belt.

The web area density is regulated by a feedback control system. The information flow of the control system is shown in Fig. 2. The web area density is continuously measured by a monitoring system that includes the Laser Scanner and the Retro-reflector. The signal from the monitoring system is fed to the control computer. The computer calculates the web area density distribution in both the MD and CD with the desired values. According to the differences between the measured values and the desired values, the computer controls the DC motor and the stepper motors to adjust the web area density distribution in MD and CD respectively.

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3. The On-line Monitoring System

In a feedback control system, an on-line monitoring device is required to measure the web area density distribution in real-time. The measurement must be carried out in both MD and CD. There has been intensive research in this area and numerous monitoring techniques have been developed, including pneumatic methods [7], radioactive methods [8, 9, 10] and optical methods [6, 11, 12]. One of the latest developments is the scanned-laser technique developed in the Department of Textiles at UMIST [13]. This is a simple and accurate optical technique for lightweight webs. In this technique, a single beam of Class lIb He-Ne laser is projected onto a rotating mirror, which makes the laser beam scan the entire width of the web. The laser beam, after passing through the fibrous web, is returned by a retro-reflector, which is situated underneath the web. The returned laser beam thus passes through the web twice. The retro-reflector is made with a two-dimensional monolayer of glass spheres secured in an adhesive binder. The retro-reflector has the unique property of returning the projected laser beam along the direction of projection. Thus only one single photodiode light detector is required. The obscuring effect of the fibrous web reduces the intensity of the returned laser beam. The degree of this intensity reduction is related to the web area density. Therefore the intensity of the returned laser beam provides a measure of the web area density. This technique is able to measure the web area density distribution in both MD and CD.

A monitoring system based on the scanned-laser technique was built in the air-laying machine. The principle of the monitoring system is illustrated in Fig. 3. The laser beam scans the web width 20 times per second. The output is amplified, filtered, and presented to a 25-MHz IBM80386 Microprocessor at a sampling frequency of 4 KHz. The scanner has a constant sampling interval of 1.8 degrees. The distance between the scanner and the retro-reflector is adjusted to be 860 mm and this gives a total of 20 measurement points across the web width.

The number of measurement points within each web sample in CD during one scan, $Y$, is inversely proportional to the number of web samples across the web width, $N$:

$$Y = \frac{20}{N}$$  (1)

The number of measurement points within a web sample in the MD, $X$, is related to the speed of the conveyor belt, the scanning speed and the sample length:

$$X = \frac{fL}{V_b}$$  (2)

where:

$f$ = the scanning frequency;
$V_b$ = the conveyor belt speed (m/sec);
$L$ = the sample length (m).

The scanning frequency was 20 scans/sec as determined by the Laser Scanner System. The sampling length can be set according to the quality requirement of the web. Once $L$ is set, $X$ will only depend on the speed of the conveyor belt.

The mean area density of a web sample can be calculated using the following equation:

$$W = \frac{1}{XY} \sum_{x=1}^{X} \sum_{y=1}^{Y} S_{xy}$$  (3)

where:
i = MD coordinate of a web sample;  
j = CD coordinate of a web sample;  
x = MD coordinate of the measurement point;  
y = CD coordinate of the measurement point;  
$W_{ij}$ = the mean web density of sample (i, j);  
$S_{xy}$ = the web density at measurement point (x, y).

4. Performance of the Monitoring Device

The stability of the signal response of the monitoring device, both short-term and long-term, is critical to the accuracy of measurement, which in turn determines the effectiveness of the control system. The short-term stability is tested within 20-second intervals. Fig. 4 shows the signal response at three different transmissions, 62.5%, 16% and 0.36%. The transmission level was simulated by using neutral density filters. A higher transmission level corresponds to a lower web area density. The coefficient of variation is 0.1%, 0.3% and 2.4% respectively for the three transmission levels of 62.5%, 16% and 0.36%. The short-term signal variation is caused by system noise. As the transmission level becomes lower, the signal response becomes weaker and the relative significance of noise becomes greater. However, even at 2.4% variation, this short-term stability of the system is generally sufficient for the purpose of controlling the area density distribution in a nonwoven web.

The signal response of the monitoring system must also have sufficient long-term stability, or repeatability, for the system to function properly. Due to various reasons, possibly including the variation of the environmental conditions, the variation of the properties of the photo detector and the gain of the amplification circuit of the system, the signal response of the system was found to have a significant long-term drift. This signal drift is defined as:

\[ \Delta S = S_t - S_0 \]  

where

\[ \Delta S = \text{the signal drift at the measurement point}, \]

\[ S_t = \text{the measured signal at time } t, \]

\[ S_0 = \text{the signal at time } \theta \text{ (reference time)}. \]

4.1. Relationship between Signal Drift and Web Area Density

Fig. 5 shows the relationship between the signal drift within the web forming area and the drift at a reference point. The reference point is located just beyond the web forming area so that the signal response from this point is not affected by the variable web area density. Five different web area densities are shown in Fig. 5. The relationship between the signal drift at measurement points and the drift at the reference point is approximately linear and it can be expressed as:

\[ S_t - S_0 = K \Delta S_r \]  

where

\[ \Delta S_r = \text{the signal drift at the reference point}. \]

Rearranging equation (5):

\[ S_0 = S_t - K \Delta S_r \]  

It can be seen from Fig. 5 that the value of \( K \) is dependent on the web area density that can be measured by \( S_t \). Through regression analysis of the data for Fig. 5, a linear relationship between \( S_t \) and \( K \) was found:

\[ K = -0.206S_t + 0.162 \]  

From (6) and (7):

\[ S_t = S_0 - (-0.206S_t + 0.162)\Delta S_r \]  

Using equation (8), the signal, \( S_t \), of any given time \( t \), can be converted to the signal, \( S_0 \), of a fixed reference time \( \theta \). \( S_0 \) is used by the control system as the control signal. This means that the control system is not affected by any drift because it is
based on the signal measured at the same reference time. In order to calculate $S_b$, the value of $\Delta S$, is also calculated in real-time for every measurement cycle.

5. Control Mechanisms

In the MD, the feedback control of web area density can be achieved by adjusting the speed of the conveyor belt according to the signal generated by the on-line monitoring system. This is similar to established techniques used for the auto-leveling of sliver linear density. The DC motor shown in Fig. 1 drives the conveyor belt and the computer controls the DC motor and consequently the conveyor belt speed.

In the CD, the web area density distribution depends on the velocity distribution of the airflow field across the machine width and the fiber concentration distribution in the airflow that is related to the fiber feed and the operation of the card. The variation of the web density in the web formation area leads to the local variation of airflow resistance. When the web is thicker in an area, the resistance will be larger and consequently the airflow will be smaller. This changes the distribution of the airflow and provides a self-regulating effect for the web density. However, it can be concluded from a study by Hoerer [14] that the self-regulating effect is very limited for a low-density web that has a low solidity ratio. This effect is even more limited for a moving thin web that passes through the fiber deposit area quickly and provides little time for the self-regulating effect to take place. Experimental results shown in Fig. 8 confirm that the influence of the self-regulating effect is smaller when the web becomes thinner as the 11 g/m² web is much more uneven than the 75 g/m² web. To control the density of a thin web effectively, extra regulating mechanisms are required.

Fig. 6 compares the signal responses before and after the correction over a period of 60 hours when no fibre web was present. Fig. 7 compares the signal responses when a 34 g/m² of web was present. When the signal response is at a higher level, corresponding to a thinner web, the long-term signal drift accounts for a smaller percentage and is less influential to the nonwoven web measurement. However, when the signal response is at a lower level, corresponding to a thicker web, the long-term signal drift will have more influence on the measurement. This is a limitation of the laser monitoring system and it was indicated that a laser monitoring system is mainly suitable for webs of which the density is less than 60 g/m² [13].

![Fig. 6. The long term drift of the monitoring system without nonwoven web](image)

![Fig. 7. The long term drift of the monitoring system with a 34 g/m² web](image)

![Fig. 8. Comparison between the self-regulating effects at different web area densities](image)

Web density: Web A = 11 g/m²; Web B = 75 g/m².
To be able to regulate the airflow across the machine width, the whole width of the suction box is divided into 20 sections using a vane system (Fig. 9). The principle of the vane system is shown in Fig. 10. The 20 sections are grouped into 5 groups. The gap between two adjacent vanes in the same group is:

\[
a = \sqrt{l^2 + \left(\frac{1 - d}{2}\right)^2 - 2l\left(\frac{1 - d}{2}\right)\cos \alpha - \frac{d}{2}} \quad (9.\text{a})
\]

for \(0 \leq \alpha \leq \cos^{-1}\left(\frac{l - d}{2l}\right)\);

\[
a = l \sin \alpha - \frac{d}{2} \quad (9.\text{b})
\]

for \(\cos^{-1}\left(\frac{l - d}{2l}\right) \leq \alpha \leq \sin^{-1}\left(\frac{l - d}{2l}\right)\);

\[
a = l - d \quad (9.\text{c})
\]

for \(\sin^{-1}\left(\frac{l - d}{2l}\right) \leq \alpha \leq \pi\).

where:
- \(l\) = the distance between two adjacent vane shafts;
- \(d\) = the vane shaft diameter;
- \(\alpha\) = the opening angle of the vanes in relation to the plane formed by the axes of the vane shafts.

Fig. 9 shows the overview of the vane system

Fig. 10. The principle of the vane system

Fig. 11 shows the relationship between the local solidity ratio and the angle of the vanes for various values of \(d/l\). When the distance between the vanes is smaller (larger \(d/l\)), or in other words when there are more vanes within a given space across the machine width, the solidity ratio changes more slowly with the angle of the vanes. This means that the solidity ratio and thus the pressure loss can be more finely regulated when more vanes are used, but the effective range of regulation decreases with the increase of the number of vanes. In this project, the value of \(d/l\) was chosen to be 0.34. The vane angles in different groups are controlled automatically by the computer according to the local web area density measured by the on-line monitoring system. The computer calculates the difference between the required web area density and the measured web density. If the measured web area density is higher than the required value, the vane angle in the corresponding group is reduced to increase the local solidity ratio; if the measured web area density is lower than the required value, the vane angle in the corresponding group is increased to reduce the local solidity ratio. This procedure is progressive and iterative.

Fig. 12 shows the system response when the area density of the feed lap was increased by 100% across one fifth of the machine width at section 5. The nominal output web density was 10 g/m². Without the control system, the web density across the machine width becomes very uneven. The web density increases sharply in section 5, as well as section 4. The web density increase in section 4 indicates that there is fibre spreading across the machine width during carding and in the transporting airflow. The CV% of the web density is above 8%. The average web density along the machine direction is increased, corresponding to the increased fibre input. Once the control system is activated, the web density across the machine width becomes much more even, with a CV% of around 4%. The web density along the machine direction is also brought back to the nominal value.

6. Conclusions

The area density distribution in air-laid nonwoven webs is one of the most important parameters that determine the property of the final nonwoven product. It is particularly
critical for lightweight webs where the self-regulating effect is very limited. It has been shown that the web area density distribution in both the machine direction and the cross-machine direction in air-laying nonwoven processes can be controlled on-line. The web density is monitored in real-time. The machine direction control is achieved by controlling the speed of the transporting belt and the cross-machine direction control is achieved by controlling the airflow using a vane system in the suction chamber.

\[ \text{Fig. 11. The relationship between solidity ratio and vane angle} \]

\[ \text{Fig. 12. The system response to uneven feed density} \]

7. List of Symbols

- \( \alpha \): vane angle to the plane of the vane shaft axes.
- \( a \): gap between two adjacent vanes in the same group.
- \( d \): vane shaft diameter.
- \( f \): scanning frequency of laser beam.
- \( k \): MD coordinate of a web sample.
- \( j \): CD coordinate of a web sample.
- \( t \): distance between two adjacent vane shafts.
- \( L \): sample length.
- \( N \): number of web samples across the web width.
- \( \Delta S_y \): web density at measurement point \((x, y)\).
- \( \Delta S_r \): signal drift at reference point.
- \( V_b \): conveyor belt speed.
- \( W_y \): mean web density of sample \((i, j)\).
- \( x \): MD coordinate of measurement point.
- \( X \): number of MD measurement points within a web sample.
- \( y \): CD coordinate of measurement point.
- \( Y \): number of CD measurement points within a web sample.

References