Optimum separation of machine-direction and cross-direction product variations

The scanning measurement challenge

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Faster scanning, parallel measurement data processing, and adaptive profile trending permit higher-frequency MD and CD measurement without compromising the speed or accuracy of control profile determination.

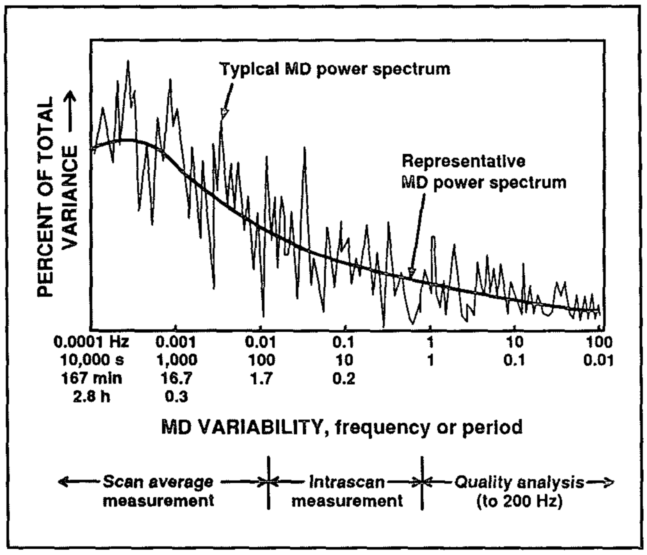
Paper quality variability is measured and controlled in two dimensions: the machine direction (MD) and the cross direction (CD). During the production process, the former varies with respect to time (*1*) and the latter with respect to both time and cross-machine position. The ultimate goal of supervisory measurement and control systems is to successfully control the entire spectrum of product quality variations, from the very narrow and short-term to the very broad and long-term. While low-frequency variations (with respect to both time and space) are relatively easy to identify and control, high-frequency variations represent a difficult challenge.

Before high-frequency variations can be controlled and eliminated, they must be "seen" or measured by the system. A scanning measurement system cannot possibly measure 100% of the sheet; only a portion of the sheet is "sampled" and presumed to represent the entire product. As with any sampling exercise, the more samples taken, the greater the accuracy of the statistically-based estimate. Increasing the sample "population" with a scanning measurement system requires an increase in the rate at which measurements are taken.

MD and CD measurement resolution has increased significantly in the last few years. Previously with scan-average MD measurement, the highest measurable frequency was in the region of 0.017-0.025 Hz (a 40-60-s period, equal to approximately twice the scan time). As illustrated in **Fig. 1**, intrascan measurement, and quality analysis systems, have increased process visibility to include MD frequencies as high as 200 Hz. In addition, improved CD measurement techniques now enable profile measurements as fine as 1 cm wide. These improvements are the combined result of faster, more precise sensor signal processing, faster scan speeds, and innovative computational methods.

When a sensor scans the sheet, it traces a diagonal path, measuring a "now" profile that includes both MD and CD variations. As illustrated in **Fig. 2**, MD variations may

1. Typical paper machine MD power spectrum



be erroneously perceived as CD variations unless they are somehow isolated and removed from the final measured profile.

Until imported MD variability is eliminated from the measured profile, "true" profile changes cannot be confidently identified and successfully controlled. Removal of unwanted MD variability from the profile may be accomplished by weighting the measurement at each cross-direction position to the long-term historical value rather than the most recently measured value. This conventional procedure is referred to as exponential multiple-scan trending. In its basic form, exponential profile trending is quite simple and can be described by a single mathematical parameter— the trend factor. As noted in **Fig. 3**, when a trend factor of 0.2 is used, 20% of the most recent value will be added to 80% of the historical value to derive the trended measurement.

As Fig. 3 illustrates, with a 0.2 trend factor it would take approximately 10 scans to register 90% of a step-wise profile change. By comparison, if low MD variability

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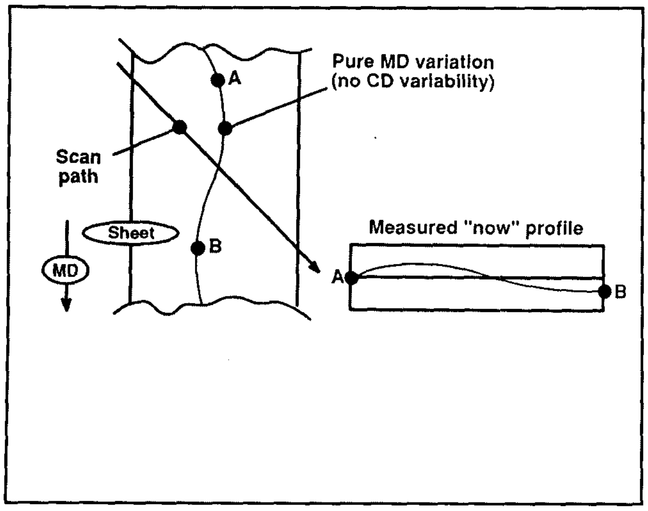
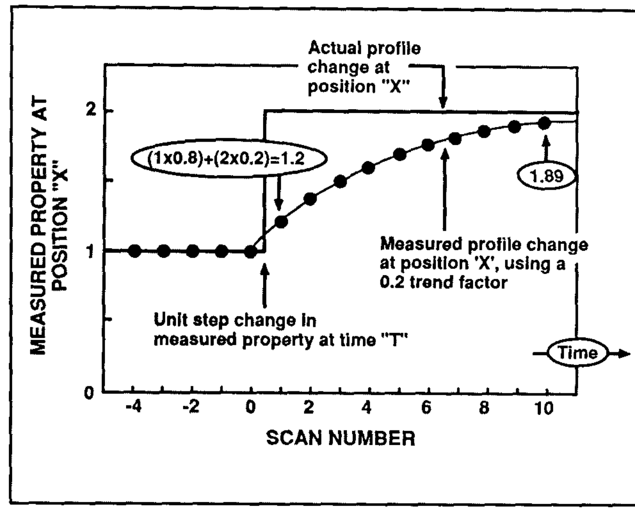
2. Diagonal scan path introduces MD variations into "now" profile.



3. Exponential profile trending



permitted the use of a more aggressive 0.3 trend factor, about 90% of the unit profile change could be detected in only 6 scans, to provide 40% faster profile measurement response.

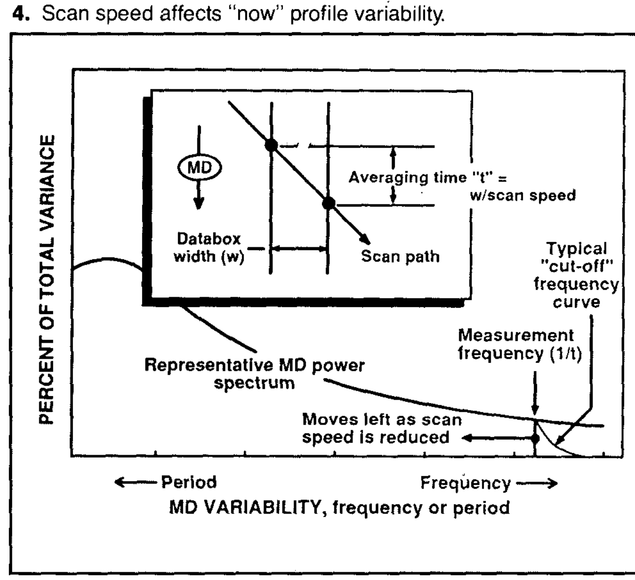
The ongoing development of higher-resolution measurement technologies increases the importance of methods used to eliminate MD variability from cross-direction profiles prior to trending. Without effective alternatives, increasing measurement resolution will necessitate more conservative exponential trending, resulting in slower profile measurement and control response. Of course, this would be undesirable. The remainder of this paper will review various techniques designed to improve the response of high-resolution measurement systems to "true" profile changes.

The scanning measurement challenge

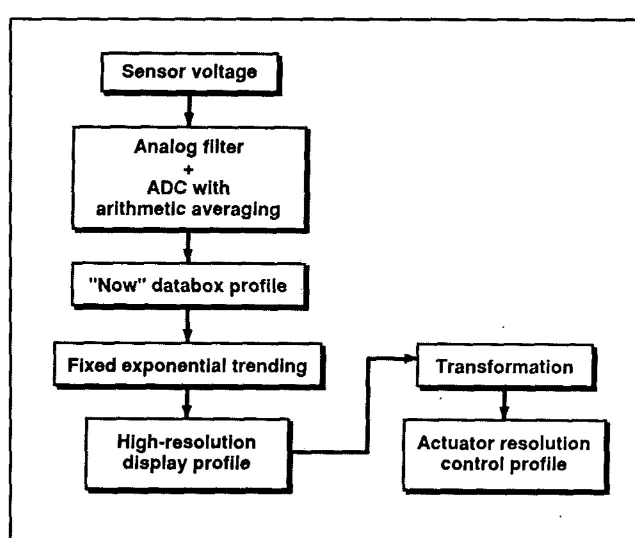
The scanning measurement challenge is to ensure that advances in measurement resolution do not compromise the speed and accuracy of CD profile measurement and control. New, effective ways to quickly remove MD variations from the CD profile are required. One suggested way to accomplish this is to scan more slowly to increase the averaging time for each cross-direction measurement zone (often referred to as a databox or minislice) (*2*). As the scan speed is decreased, the "cut-off" frequency, shown in **Fig. 4**, moves to the left, thereby reducing the amount of high-frequency MD variability that may be introduced into the "now" profile. Unfortunately, while fewer scans will be required to "trend-out" the remaining MD variability, the time required to complete each scan increases proportionally. The net effect is a trade-off between measurement speed and accuracy. In addition, decreasing scan speed reduces MD measurement resolution directly, opposing new high-speed measurement efforts such as intrascan MD measurement.

As illustrated in **Fig. 5**, this slow-scanning method typically employs serial measurement data processing. An analog filter first attenuates the sensor signal (to reduce sensor signal noise), then an analog-to-digital converter (ADC) samples the residual signal approximately every 10 ms. Finally, *n* samples are averaged within a databox

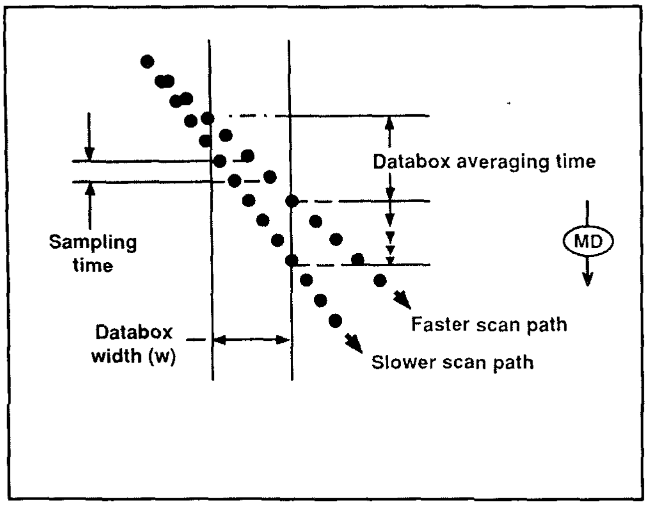
4. Scan speed affects "now" profile variability.



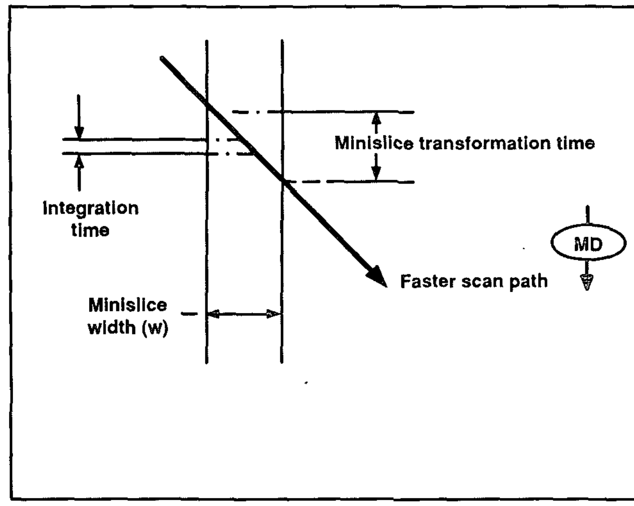
5. Serial measurement data processing



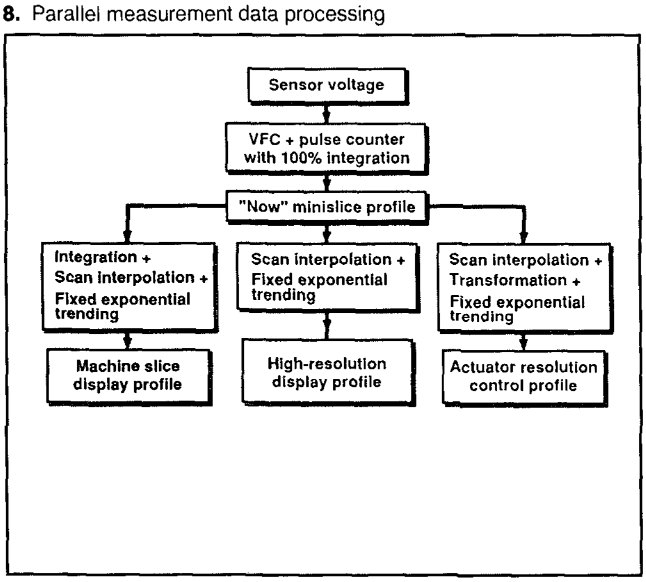
6. Alternative signal processing techniques: signal sampling



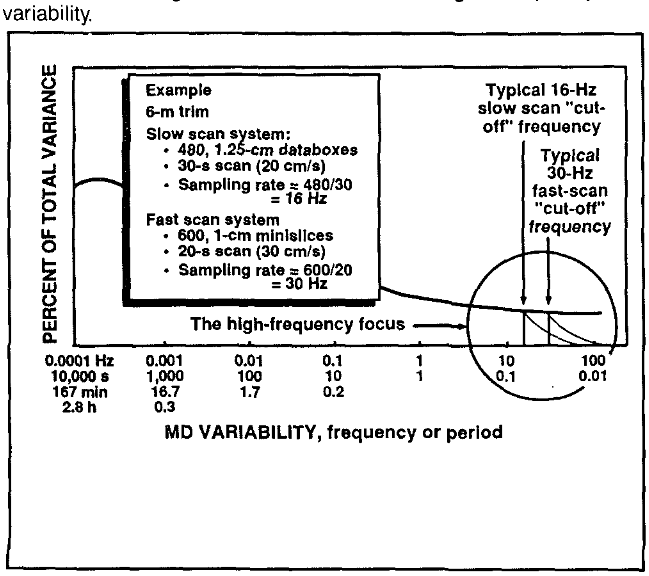
7. Alternative signal processing techniques: signal integration



8. Parallel measurement data processing



9. Faster scanning enables measurement of higher-frequency MD variability.



to produce the databox measurement. As shown in **Fig. 6**, slower scanning improves the accuracy of this sampling technique by increasing the number of samples per databox.

An alternative method uses faster scanning to trend-out MD variability more quickly by completing multiple scans in less time. This fast-scanning technique employs a 512-kHz voltage-to-frequency converter (VFC) and a pulse counter to integrate pulses every 6.25 ms. By integrating 100% of the sensor signal (**Fig. 7**), much of the spurious variability ("noise") generated by sampling techniques is eliminated to provide a more accurate measurement. As a result, faster scan speeds can be used without compromising accuracy.

Parallel measurement data processing

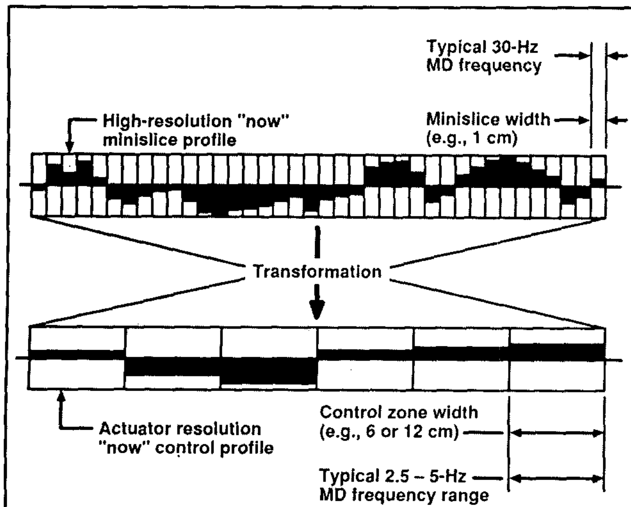
From a profile control standpoint, the measurement system's goal is to develop accurate actuator resolution profiles as quickly as possible, allowing faster response to process transients following breaks or grade changes. By comparison, analytic exercises like streak analysis, which use higher-resolution profiles (down to 1 cm), are not particularly time-critical. As shown in **Fig. 8**, the fast-scanning method satisfies each specific requirement by processing "now" minislice data (equivalent to databoxes) through different channels for different end uses.

Faster scanning enables higher-frequency MD measurement (**Fig. 9**). While this is desirable for MD measurement and control purposes, it will increase the "now" minislice or databox profile variability.

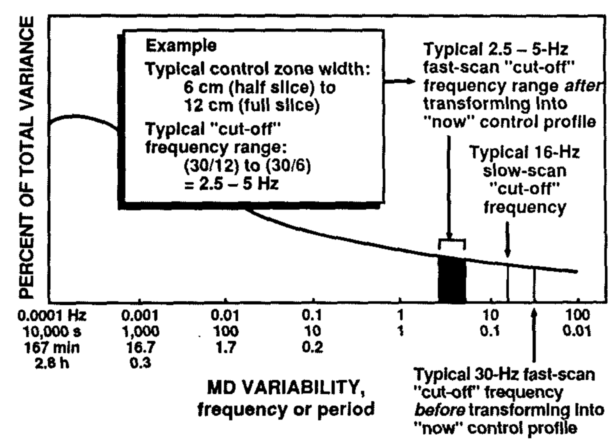
To compensate for the increased MD variability imported into the "now" minislice profile, parallel measurement data processing transforms it into the appropriate actuator resolution control profile prior to trending (**Fig. 10**). This simple exercise immediately removes much of the unwanted MD variability from the "now" control profile. Consequently, less trending, fewer scans, and less time is required to accurately measure control profile changes.

By comparison, because high-resolution "now" measurement profiles must contain more MD variability, trending from "now" databoxes into databox profiles (as shown in

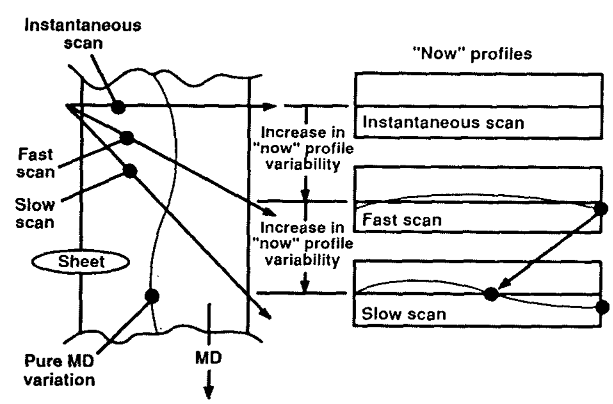
10. Transforming "now" minislice profiles into "now" control profiles



11. Transforming into "now" control zones before trending reduces the effect of high-frequency MD variability.



12. Reducing scan speed in the presence of low-frequency MD variations will increase the apparent cross-directional variability of the "now" profile.



13. Faster scanning attenuates low-frequency MD variability.

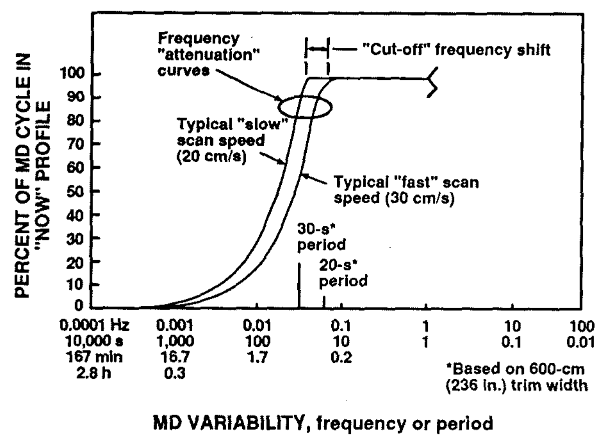
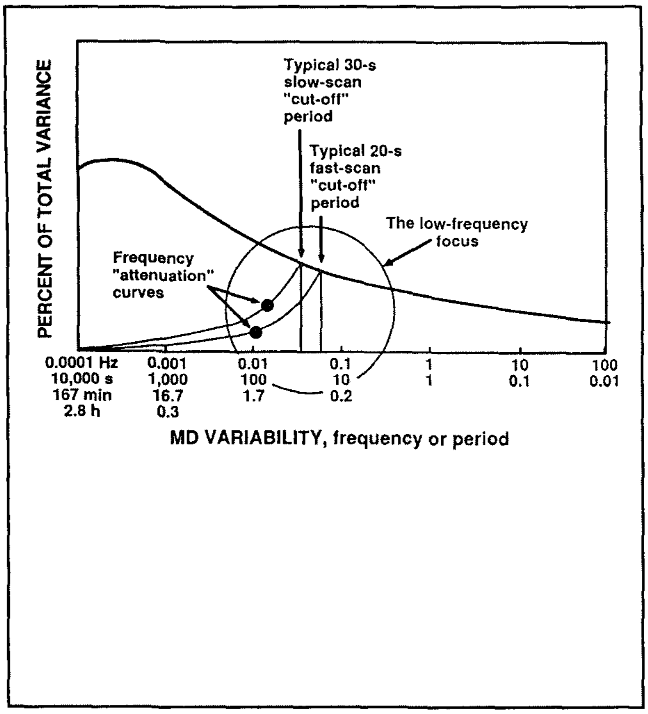


Fig. 4) requires more scans, and hence more time, to determine "true" profile changes. The relative benefit of trending before and after control-zone transformation is illustrated in **Fig. 11**. Transforming into control zones moves the "cut-off" frequency far to the left, significantly reducing the amount of MD variability that may be introduced into the "now" control profile.

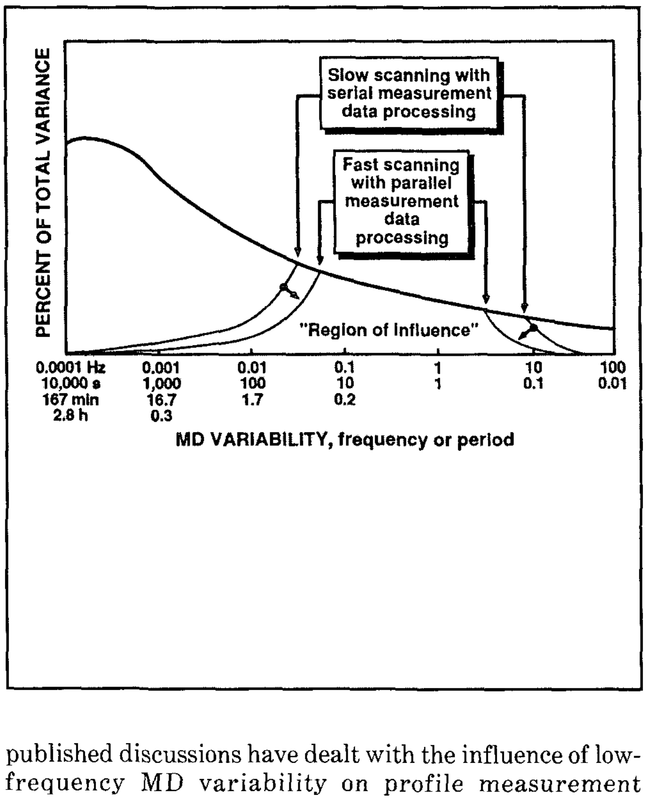
The influence of low-frequency MD variability

The foregoing discussion focused on the relative merits of various scanning measurement techniques used to eliminate high-frequency MD variability from CD profiles. This "high-frequency focus" has been the topic of many recent technical papers (*2–4*). However, few

14. Scan speed affects low-frequency variability of "now" profiles.



15. The overall "region of influence" is reduced by fast scanning and parallel measurement data processing.



published discussions have dealt with the influence of low-frequency MD variability on profile measurement response and accuracy.

As illustrated in **Fig. 12**, slower scanning increases the apparent CD spacial frequency of imported MD variations. Consequently, reducing scan speed in the presence of low-frequency MD variations will increase the apparent cross-directional variability of the "now" profile, making it more difficult to quickly determine accurate CD profiles.

This phenomenon is illustrated mathematically in **Fig. 13**. As the scan speed is reduced, more of an MD variation will be measured within a single scan. For example, with a 20-cm/s scan rate on a 600-cm-wide sheet, 1.5 cycles of a 0.05-Hz MD variation would be imported into each "now" profile, whereas when the scan speed is increased to 30 cm/s only one complete cycle would be imported into each "now" profile.

As the scan speed is increased, the "cut-off" period shown in **Fig. 14** moves to the right, thereby reducing the amount of low-frequency MD variability introduced into the "now" profile. Faster scanning essentially attenuates the spacial frequency of imported low-frequency MD variations so that less trending is required, resulting in faster, more accurate control profile determination.

The "region of influence" concept

By combining the low- and high-frequency focuses, it is possible to define a "region of influence" bounded by the low and high "cut-off" frequencies or periods shown in Figs. 9, 11, and 14. The size of this region of influence is indicative of the amount of MD variability that must be removed from the "now" profile by multiple-scan exponential trending. Consequently, the larger the region of influence, the more scans and time will be required to develop accurate control profiles. As illustrated in **Fig. 15**, the combined advantages of faster scanning and parallel measurement data processing should result in a smaller region of influence and hence the ability to more quickly and accurately measure profile changes.

Adaptive profile trending

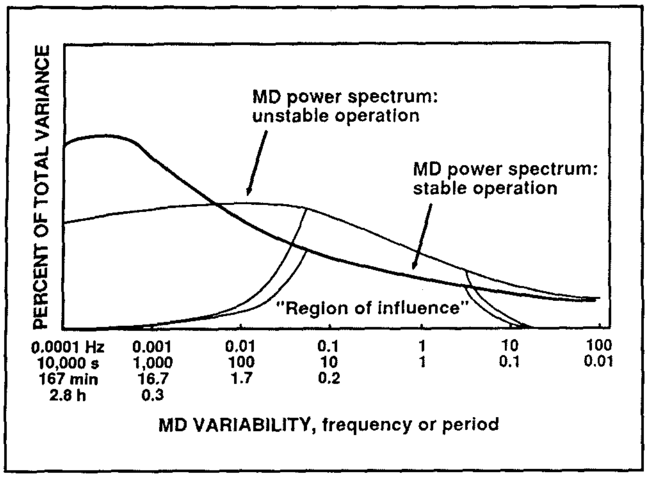
After the "now" minislice profile is transformed into the "now" control profile, residual MD variations must be "trended out" to derive the "true" CD profile. The ideal amount of trending will be proportional to the bounded area under the MD power spectrum curve, defined as the region of influence in Fig. 15. At times, if the paper machine is quite stable, the region of influence might be small, while at other times, such as after a break or grade change, the region of influence might be quite large (**Fig. 16**). Consequently, the ideal amount of trending for any paper machine will vary with process conditions.

In recognition of this, rather than using a fixed trend factor (Fig. 3), adaptive trending uses a proprietary, patented (*5*) procedure to automatically match the trend factor to the size of the region of influence, on a zone-by-zone basis, at the end of every scan. This approach enables faster recognition of "true" profile changes and heavier trending of transient product variations that are too short-term for the control system to correct.

Conclusions

To effectively measure and control cross-direction paper quality variations, MD variability must be quickly and thoroughly removed from control profiles. A wide range of MD variations exists on the paper machine, so measurement techniques must be designed to remove both

16. The size of the region of influence varies with process conditions.



low- and high-frequency MD variability from control profiles.

The concept of a "region of influence" bounded by low and high "cut-off" frequencies characteristic of the measurement system design has been introduced to aid in the value analysis of alternative cross-direction measurement technologies.

Faster scanning and parallel measurement data processing have been shown to reduce the region of influence, allowing faster, more accurate profile determination.

As higher-resolution measurement technologies evolve, additional innovations designed to further reduce the region of influence may be required to maintain and improve profile measurement and control effectiveness.□

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