Dynamic Textile Process and Quality Control Systems

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Abstract

The paper attempts to develop a *"Dynamic Process and Quality Control System* (DTPQCS)" for staple spinning process that are serially connected with time lags. This new system provides process averages and control limits that are relative to the conditions of the prior processes via structural relationships that connect the factors in a given process stage to that of the next stage. By obtaining more accurate control limits, the root causes of the out of control situations will be determined precisely, and unnecessary corrective actions (false positives) that are detrimental to quality monitoring and improvement will be minimized.

The major research task was to research and identify all published papers and sort out clearly defined input and output parameters that are essential for controlling process performance and product qualities. The challenge is to align and consolidate the equations to a single set at each stage in such a way that a dynamic system can be developed by combining all process steps in sequence, linking all input and outputs parameters. An approach under development attempts to consolidate the multiple structural equations obtained by different researchers into one manageable equation. In the j^{th} process, the output Y_j is expressed as a function of Y_{j-1} of the previous process and 'm' new input factors $\underline{z}_j\ (z_{j1}, z_{j2}, \ldots, z_{jm})$;

$$Y_j = f_j(Y_{j-1}, z_j), \quad j = 1, 2, 3, \ldots, k$$

In any given two contiguous processes, the input ($\underline{z}$) and output (Y) relationships are more than one in most cases. With 'P' structural equations with certain number of factors, each structural equation may be rewritten as a polynomial function for finite solutions or an iterative solution. Progress to this point is included here.

Key Words: Dynamic process control system, Structural relationship, Variance tolerancing, Control limits, Fusion algorithm.

Introduction

Development of textile science and engineering during the last 100 years has been truly remarkable based on the published research reports and claims. The literature and structural equations found to date are indeed quite impressive in their scope and application potentials. However, the structural models and prediction equations known to date are seldom used in quality and process control practices in the US or elsewhere. Why?

Textile quality control often involves keeping output of individual processes in control though the use of Shewhart control charts [2]. Although textile producers have invested in quality control systems through Shewhart control methods, manufacturers have yet to experience a significant cost reduction or increased benefits. This is mainly due to the use of control systems that are static and inflexible for accommodating the complex, dynamic and interactive nature of textile production environment. Frequent false alarms and unwarranted process calibrations based on the "single stage control algorithms," often built in the manufacturing equipment, have resulted in loss of production time, materials and consequently profit. In case of an out-of-control situation, the backtracking of the problem source naturally begins with the last machine where the problem is caught [1, 3]. This is known as feedback control, which often accompanies instability with a tendency for over-control or unwarranted calibration.

In addition, a feedback control in textiles often leads to disappointing guesswork rather than an effective corrective action due to 1-to-N nature of manufacturing processes [4]. Thus, use of a static target reference in a continuous, dynamic textile process causes frequent false alarms when the changes in process averages originate from the prior process stages. To remedy this difficulty, a dynamic EWMA control chart procedure [5, 6] can be employed. However, this procedure was somewhat effective only for short-run process control situations as it forces us only to examine only the current process average against the target with no reference to the biases generated by the prior processes [2] indefinitely. This undoubtedly is a terribly inefficient control process completely void of structural relationships already known for the causes and effects.

Therefore a dynamic quality control system for dry and wet textile processes is being developed as an entirely new attempt to apply the known structural equations published during the last 60 years. The task is to align and consolidate the equations to a single set at each stage in such a way that a dynamic system can be developed by combining all process steps in sequence, linking all input and outputs parameters. This task is quite challenging but most rewarding.

By obtaining more accurate control limits, the root causes of the out of control situations will be determined precisely and unnecessary corrective actions (false positives) that are detrimental to quality monitoring and improvement will be minimized. The conventional quality/process management based on Shewhart control scheme and the so-called "feed-back" and "feed-forward" control system has had only limited success in textile manufacturing in the past. These "failure mechanisms" have been outlined by Suh [1]. The key missing links are the structural relationships that connect the factors in a given process stage to that of the next stage. These stages may be linked through the structural equations via variance channeling as already demonstrated by Suh and Koo [12, 13]. Without implementing these relationships, the stand-alone Shewhart control systems become totally useless when the input factors have been perfectly in control and match the process averages established. Otherwise, the "in-control" or "out-of-control" decisions become either false positives or false negatives. The Dynamic Textile Process and Quality Control System is designed in order to compute the expected processes averages and the associated control limits, thus generating an optimal control strategy at each process stage.

Theoretical Framework

A conceptual/theoretical frame for a dynamic quality/process control system is being developed. The key strategy is to estimate the output process averages and variances as functions of the input process averages and also the variances originating from the prior process stages (Figure 1).

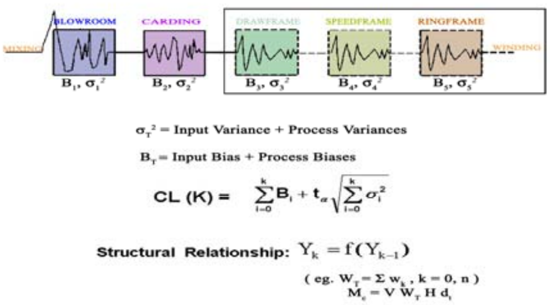

Figure 1. Conceptual frame for dynamic control limits from mixing/blending to ring frame via the structural relationships developed.

Well-known properties of fiber clusters are considered and their changes are traced between any two successive stages through the established relationships (Figure 2). Various fiber properties provide the necessary input process averages and variances of the subsequent output processes.

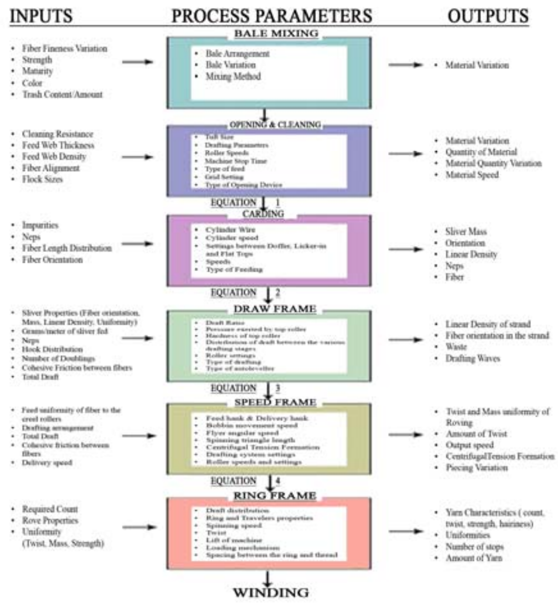

Figure 2. Framework for structural and functional relationships among key spinning processes

Approach

All scientific publications and reports available to date have been sorted out to establish the connectivity as a contiguous system within a framework of *"disjoint real-time"* domain as a requirement for *"variance tolerancing and channelling"*. This approach consists of three phases:

1. Development of Structural Relationships in Spinning

In the first stage a structural equation is developed by tying the opening and mixing processes to carding, and then to drafting and so on. For this one of the various input factors (eg: mass, strength, fineness, etc.) is considered which exhibits certain amount of variation at every stage consistently throughout the entire spinning process.

As an example, we considered the mass variation in the early stages of spinning. The output mass variation becomes the input of the subsequent stage.

a) Mass Variation in Opening & Mixing

Let *'M'* be the mass of fibers being collected from each bale by the mixing frame, *'V'* the speed at which the mixing frame collects the mass *M*, *'W'* the total width of the bales, *'H'* the height /depth of each bale, '*d*' the density of the bale and *'t'* the collection time unit.

Then we can calculate the amount of mass *M* being collected by the mixing frame in time *t* seconds as

$$M = V \cdot W \cdot H \cdot d \cdot t \quad \text{------------ (1)}$$

Now by differentiating Equation (1) with respect to time *t* we get the deviation in feed (input) i.e.,

$$\sigma_{feed} = \text{Change in mass with respect to time}$$

$$= dM / dt$$

$$\boxed{\sigma_{feed} = V \cdot W \cdot H \cdot d} \text{ ---------- (2)}$$

b) Mass variation in Carding

Let 'X ' be the deviation in web (output), 'X_p' the deviation in feed (input), $K(t)$ a function of t, 't' being the instantaneous time, 'c' the expected residence time of fiber in the card, 'q ' the weight per unit length of web (output), 'q_p' the weight per unit length of feed (input), 'Y ' the instantaneous deviations in 'q ' and 'Y_p' the instantaneous deviation in q_p.

Here, $X_{\pi} = \dfrac{Y_{\pi}}{q_{\pi}}$, $X_p = \dfrac{Y_p}{q_p}$ and $K(t) = \dfrac{e^{-t/c}}{c}$

The deviation in web (output) is given [8, 9] by equation, below

$$\boxed{\sigma_{web} = \int_0^t K(t) X_p (t - \delta)\, d\delta} \text{ ------ (3)}$$

Substituting the values of $X_{..}$ $K(t)$ and X_p in Equation (3), we obtain,

$$\sigma_{web} = \left[\frac{\int_0^t e^{-t/c}\, \sigma_{feed}\ t\, d\delta - \int_0^t e^{-t/c}\, \sigma_{feed}\ \delta\, d\delta}{c} \right]$$

$$\sigma_{web} = \left[\frac{\int_0^t e^{-t/c} (VHWd)\, t\, d\delta - \int_0^t e^{-t/c} (VHWd)\, \delta\, d\delta}{c} \right]$$

$$\sigma_{web} = \left[\frac{(e^{-t/c}\ VHWd\ t)\,(t - 0) - (e^{-t/c}\ VHWd)\,(\frac{t^2}{2} - 0)}{c} \right]$$

By letting $L = W{\cdot}H{\cdot}d$,

$$\boxed{\sigma_{web} = \frac{L}{2c} (V\ e^{-t/c}\ t^2)} \text{ ------------ (4)}$$

The coefficient of variation, denoted as V (%) based on Equation (4), is given by

$$V = \frac{\sigma_{web}}{\bar{X}}$$

where, mean $\bar{X} = V \cdot W \cdot H \cdot d \cdot t$

$$V = \frac{\frac{L}{2c} V\, e^{-t/c}\ t^2}{V\, W\, H\, d\, t}$$

$$= \frac{\frac{WHd}{2c} V\, e^{-t/c}\ t^2}{V\, W\, H\, d\, t}$$

$$\boxed{V = \frac{t}{2c} e^{-t/c}} \text{ --------------- (5)}$$

c) Mass variation in Drawing

Let 'V' be the irregularity C V, 'n' the number of doublings, 'V_0' the irregularity of the input, 'A' and 'B' the coefficients where 'A' is due to the increasing irregularity from the reduction of thickness or decrease in the number of fibers in the cross section and 'B' is due to drafting mechanism, 'N_0' the hank of input, 'z' the draft ratio and 'V_{α}' be the additional irregularity arising from roving tension at roving frames. Then, according to *the law of drafting* [10],

$$\boxed{V^2 = \frac{1}{n}\left[V_0^2 + AN_0(z-1) + BN_0(z-1)^2 z \right] + V_{\alpha}^2} \text{ --------- (6)}$$

where, $A = \varphi \dfrac{10^4}{N_f}$ and $B = \gamma^2 \varphi \dfrac{10^4}{N_f}(1 + 3c_f^{\ 2})\beta$

As V from Equation (5) is the input of the drawing process, Equation (6) becomes

$$\boxed{V^2 = \frac{1}{n}\left[\frac{t^2\, e^{-2t/c}}{4c^2} + AN_0(z-1) + BN_0(z-1)^2 z \right] + V_{\alpha}^2} \text{ ------- (7)}$$

The additional irregularity added at the roving frame is a function of the thickness of the input strand, the draft ratio, the number of doublings and the draw frame roller settings.

The relative variance (V_{α}^2) added by drafting at the roving frame is given [11] as

$$\boxed{V_{\alpha}^2 = \frac{AN_0}{n}\left(\frac{S - \bar{L}}{\bar{L}} \right)(z-1) + d} \text{ --------- (8)}$$

where N_0 is the hank of the input strand, z the draft ratio, n the number of doublings, S the draw frame roller settings, $\bar{L}$ the mean fiber length, d a constant and A the source of irregularity of the product.

Substituting the value of V_{α}^2 from Equation (8) in Equation (7), we get

$$V^2 = \frac{1}{n}\left[\frac{t^2\, e^{-2t/c}}{4c^2} + AN_0(z-1) + BN_0(z-1)^2 z \right] + \left[\frac{AN_0}{n}\left(\frac{S - \bar{L}}{\bar{L}} \right)(z-1) + d \right]$$

$$V^2 = \frac{1}{n}\left[\frac{t^2\, e^{-2t/c}}{4c^2} + AN_0(z-1)\left[1 + \left(\frac{S - \bar{L}}{\bar{L}} \right) \right] + BN_0(z-1)^2 z + nd \right]$$

$$\boxed{V^2 = \frac{1}{n}\left[\frac{t^2\, e^{-2t/c}}{4c^2} + \frac{AN_0(z-1)\, S}{\bar{L}} + BN_0(z-1)^2 z + nd \right]}$$

$$V^2 = \frac{1}{n}\left[\frac{t^2\, e^{-2t/c}}{4c^2} + AN_0(z-1)\left[\frac{S}{\bar{L}} \right] + BN_0(z-1)^2 z + nd \right]$$

--------- (9)

2. Fusion Algorithm for Multiple Structural Equations (FAMSE)

In order to consolidate N multiple structural equations, that may exist between the input and output variables, the output y_j at j^{th} process stage is expressed as a function of Y_{j-1} of the previous process and 'm' new input factors z_j $(z_{j1}, z_{j2}, \ldots, z_{jm})$. Through an iteration approach, a new algorithm is being developed in order to obtain one (ultimate) structural equation from the 'N' original sets;

$\left[Y\right]_{1\times1} = \left[A^*\right]_{1\times k}\left[X\right]_{k\times1}$, where $\left[A^*\right]_{1\times k}$ is a consolidated form of $\left[A\right]_{N\times k}$ and

$$\left[Y^T\right]_{1\times N} = \left[y_1, y_2, y_3, ..., y_n\right] \text{, with}$$

$$\left[X^T\right]_{1\times k} = \left[1, X_1, X_2, X_3, ..., X_{k-1}\right].$$

$$\left[A\right]_{N\times k} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 \; .... & 0 \\ a_{21} & a_{22} & a_{23} & 0 & 0 \; .... & 0 \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 \; .... & 0 \\ . & . & . & . & . \; .... & . \\ . & . & . & . & . \; .... & . \\ a_{N1} & a_{N2} & a_{N3} & a_{N4} & a_{N5} \; .... & a_{Nk} \end{bmatrix}$$

3. Variance Tolerancing and Variance Channeling

Variance tolerancing is achieved from a unique functional relationship between the input and output variables by computing the variance of the output function based on the variances of the input parameters. Based on the final structural equation from FAMSE, a set of dynamic upper and lower control limits will be constructed at each process stage. A bias B_k at the k^{th} stage is sum of all biases generated up to that stage.

$$\boxed{Var(Y) \approx \sum\left(\frac{\partial f}{\partial X}\right)_0^2 Var(X_i) = \sum f_i^2 Var(X_i)}$$

As a final step, a set of dynamic control limits responsive to the time-dependent biases will be constructed. These cumulative biases and variances are used to establish dynamic process control limits.

Variance Tolerancing – Case for Roving

The output mass variation is being determined at every stage of the spinning process in terms of the input mass variation. Here, the "input and output variances" constitute the factors linking the structural equations. Using FAMSE, several equations from the literature can be combed into a single equation at every process stage in order to generate a single structural equation. For the roving process, the variance tolerancing and channelling are accomplished by estimating the variance of the "output mass variance" as a function of the input variances from the previous processes as follows.

The coefficient of variation at a roving frame can be expressed by Equation (9) as

$$V_o^2 = \frac{1}{n}\left[V_i^2 + \frac{AN_0(z-1)\,S}{\bar{L}} + BN_0\,(z-1)^2 z + nd\right],$$

where V_o^2 is the output variance and $V_i^2 = \dfrac{t^2\, e^{-2t/c}}{4c^2}$ the input variance.

For variance tolerancing, we need to compute the variance of V_o^2, that is, we must calculate

$$Var[V_0^2] = \frac{1}{n^2} Var[V_i^2]$$

(since the other terms are constants).

By letting, $t/c = x$,

$$\text{Var}\,[V_o^2] = \frac{1}{n^2} Var\left[x^2 e^{-2x} + P_2 + P_3 + P_4\right]$$

$$= \frac{1}{n^2} Var\left(x^2 e^{-2x}\right) + \text{Constant.}$$

Here, $Var\left(x^2 e^{-2x}\right)$ can be expanded by using a Taylor's series $\sum_{n=0}^{\infty} \frac{(x-a)}{n!} f^n(a)$ with a = μ:

$$f(x) = f(\mu) + \frac{(x-\mu)}{1!} f'(\mu) + \frac{(x-\mu)^2}{2!} f''(\mu) + ...$$

$$E\left[f(x)\right] = E\left[\mu^2 e^{-2\mu}\right] + E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + ...$$

$$= \mu^2 e^{-2\mu} + 0 + \frac{\sigma^2}{2!} f''(\mu) + ...$$

$$E\left[\{f(x)\}^2\right] = E\left[\mu^4 e^{-4\mu}\right] + E\left[\frac{(x-\mu)}{1!} f'(\mu)\right] + E\left[\frac{(x-\mu)^2}{2!} f''(\mu)\right] + ...$$

$$= \mu^4 e^{-4\mu} + 0 + \frac{\sigma^2}{2!} f''(\mu) + ...$$

$$\text{Var}\,[V_o^2] = \frac{1}{n^2}\left[E\left[x^4 e^{-4x}\right] - \left(E\left[x^2 e^{-2x}\right]\right)^2\right]$$

$$= \frac{1}{n^2}\left[\mu^4 e^{-4\mu} + \sigma^2 e^{-4\mu}(6\mu^2 - 16\mu^3 + 8\mu^4)\right]$$

$$- \left[\mu^2 e^{-2\mu} + \sigma^2 e^{-2\mu}(1 - 4\mu + 2\mu^2)\right]^2$$

Equation (10) below gives us the output variance of the "mass variance of roving" as a function of the input mean μ and the input variance σ for $x = t/c$, as defined.

$$\text{Var}\,[V_o^2] = \frac{1}{n^2}\Big[e^{-4\mu}\{\sigma^4(8\mu - 20\mu^2 + 16\mu^3 - 4\mu^4 - 1)\}$$

$$+ \sigma^2(6\mu^2 - 16\mu^3 + 8\mu^4)$$

$$-\sigma\,(2\mu^2 - 8\mu^3 + 4\mu^4)\Big] \qquad \text{-------- (10)}$$

Summary

1. A conceptual framework has been proposed to construct a *Dynamic Textile Process and Quality Control System* by which the expected process average and expected process variance at the end of each process stage can be expressed as functions of the means and variances of the previous processes in order to establish a set of dynamic control limits that are responsive to the process errors (biases) of the previous processes.
2. Structural equations were developed for the mass variation observable in the early stages of staple yarn spinning. The

expected levels of "mass variance" and their variances were computed for opening/blending, carding, drawing and roving processes.

3. Variance tolerancing was attempted between the mass variations between carding/drawing and roving. While the algebraic expressions appear to be complex, the process is shown to be straightforward, thus enabling us to generate a set of dynamic control limits at the end of roving.

4. A concept was developed for creating a *"Fusion Algorithm for Multiple Structural Equations (FAMSE)"* in order to consolidate a set of disjoint, incongruent and often non-compatible multiple equations into one functional form linking the input and output of any two contiguous processes. The algorithms will be used for performing variance tolerancing and formulation of dynamic control limits.

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