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Franz et al.(10) **Patent No.:** **US 7,092,781 B2**
(45) **Date of Patent:** ***Aug. 15, 2006**(54) **METHOD OF CONTROLLING TENSION IN A WEB**

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See application file for complete search history.

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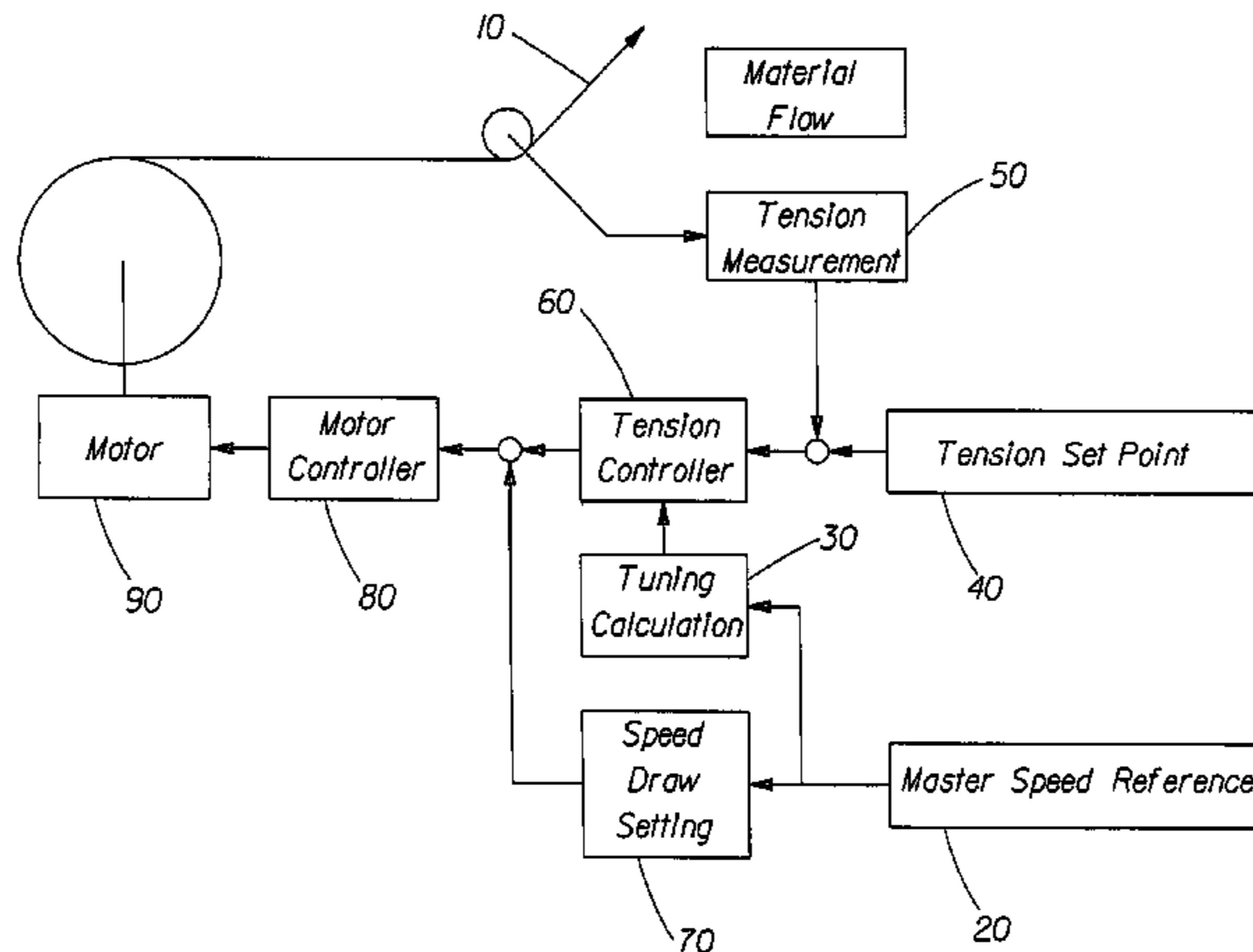
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(57) **ABSTRACT**

A method of controlling tension in a material handling process. An error signal of the process is determined. The velocity analog value of the material is determined and an instantaneous integral gain is then determined according to the velocity analog value. A proportional gain is determined. A first material parameter threshold value is determined. A first material parameter analog value is measured. The output of a controller is then adjusted according to the error signal, the instantaneous integral gain, and the proportional gain. The adjustment of a process output according to the instantaneous integral gain is controlled according to the relative values of the first material parameter threshold value and the first material parameter analog value.

20 Claims, 1 Drawing Sheet

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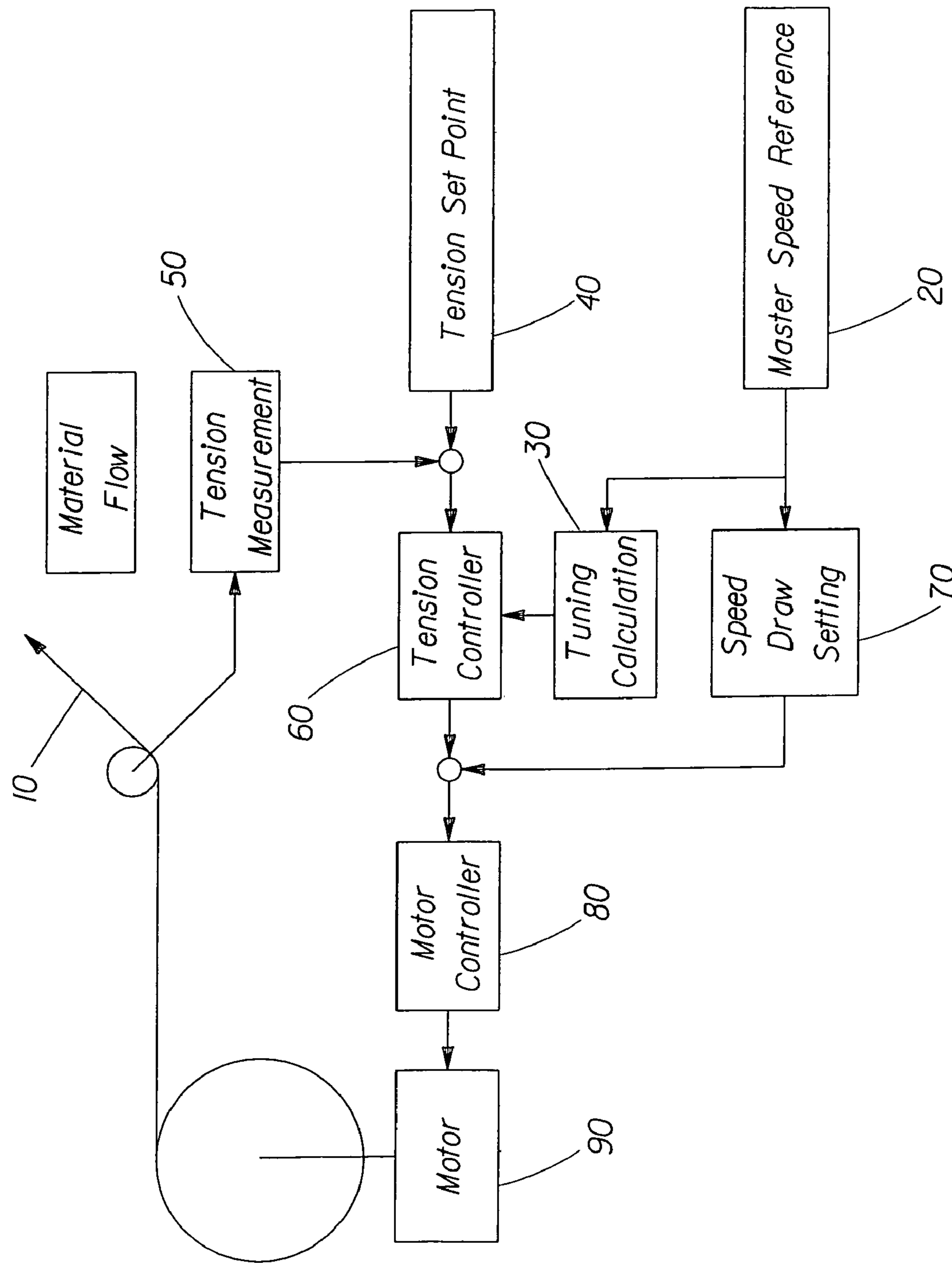
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1

**METHOD OF CONTROLLING TENSION IN
A WEB****FIELD OF THE INVENTION**

The invention relates to the control of tension in a material handling process. More particularly, the invention relates to the control of tension in a paper web during the processing of the paper web.

BACKGROUND OF THE INVENTION

A variety of manufacturing processes handle continuous materials under tension. Wire, rope, thread, fiber optic filaments, films, paper webs, metal foils, ribbon, and other continuous materials are commonly processed under tension. The material may be handled under tension during the initial phases of processing, during intermediate phases and/or in the final phase of processing into a finished product. The uniformity of the finished product in these processes may depend upon the uniformity of the tension of the material as it is processed. The processing of materials having low tensile strengths requires maintaining process tension levels within narrow ranges to prevent breakage of the material and the corresponding loss of process productivity.

Automated process controllers such as Proportional, Proportional+Integral (PI), and Proportional+Integral+Derivative (PID) controllers are used to control material tension during processing. PI, and PID controllers, calculate an error signal as the difference between a parameter set point and the measured value of the parameter. The output of the controller is then modified according to the error signal and one or more "gains" of the controller. The output is a function of the error signal and the gains. The calculation of the output may also involve constant terms. In instances where the values of controller gains are fixed, the gains are constant terms and the output is a function of the error signal. This is an iterative, feedback loop, process. The controller gains are named for their relationship to how the error signal is used. The proportional gain is used to compute output correction in proportion to the error signal. The integral gain is used to compute output correction according to the sum, or integral, of a value derived from the error signals. The derivative gain is used to compute output correction in relation to the rate of change, or derivative, of the error signal, or another signal such as the loop feedback.

Typical prior art control methods are "tuned" or optimized, by selecting appropriate controller gain values to achieve a desired process stability and rate of response. The controller gain values may be adjusted by process operators, these adjustments are manual and are related to changes in the incoming material or the process equipment performance. In some methods, the values of the controller gains are scheduled to change with the diameter of the roll of material as it is wound or unwound depending upon the specifics of the process being controlled.

Typical control methods do not provide adequate tension control at low process speeds. Typical loop tuning methods result in tension control over a speed range from a maximum speed to approximately one-tenth the maximum speed. These methods generally become too unstable and oscillatory at lower speeds. Some methods remain stable at lower speeds but sacrifice the ability to respond to rapidly changing process conditions at low speeds.

The inability to control the material tension at low speeds results in a loss of tension control during the ramp up and

2

ramp down phases of the process. Loss of control at these times results in undesirable material breaks, increased process waste, and lost productivity. The lack of adequate tension control at low speeds and also the absence of adequate control system response to changes in the modulus of elasticity of the material being processed also results in non-uniform finished products that must be disposed of as waste.

SUMMARY OF THE INVENTION

The invention comprises a method for controlling the tension of a continuous material during the processing of the material. The method provides tension control of the material over the full speed range of the process. The method controls tension as the speed, the modulus of elasticity, and/or the wound tension of the material changes.

In one embodiment the method comprises the steps of: determining an error signal in the controlled process, determining the instantaneous integral gain according to the velocity analog value of the material in process, and determining a proportional gain.

In another embodiment the method comprises the steps of: determining a set point for the tension of the material, measuring the tension of the material, determining the tension error, determining the velocity analog of the material, determining a proportional gain, determining the instantaneous integral gain of the process according to the velocity analog, and adjusting the process output according to the tension error, the proportional gain and the integral gain.

DESCRIPTION OF FIGURES

FIG. 1 is a schematic block diagram of a segment of a material handling process utilizing the method of the invention.

**DETAILED DESCRIPTION OF THE
INVENTION****Definitions:**

Controller correction calculation: the calculation made by a controller based upon an error signal, and the gains of the controller to reduce the error signal.

Error signal: the difference between a parameter set point and the measured value for the parameter.

Gain: a mathematical construct that relates a controller output, or a process unit, to a controller input.

Integral gain: a factor used in calculating the correction to the output of a process based on the integral of a value derived from the error signal. Integral gains are used in Integral controllers, Proportional+Integral controllers, and Proportional+Integral+Derivative controllers.

Instantaneous integral gain: the value of the integral gain determined by a controller tuning calculation at a particular instant in time. The instantaneous gain may be calculated at any instant according to a process variable. The value of the gain may change according to the change in the value of the variable over time. As a non-limiting example, instantaneous integral gain may be varied according to the velocity analog value of a handled material.

In one embodiment the value of the instantaneous integral gain is used directly in the controller correction calculation as the instantaneous integral gain is calculated. In another

embodiment, the value of the instantaneous integral gain may be smoothed, averaged, or filtered, using mathematical functions as are known in the art, prior to the use of the gain in the controller correction calculation. In any embodiment, a time delay may be used to offset the time of determining the value of the instantaneous integral gain and the time of the use of the newly determined value of the gain in the controller correction calculation.

Lower limit instantaneous integral gain: the value of the integral gain at a selected lower limit material velocity analog value.

Master speed reference: a master value used to synchronize speed changes across a process using multiple drives and controllers.

Maximum velocity: the maximum material velocity attainable in a material handling process.

Output: the control signal disseminated to the object(s) of a controller.

Proportional gain: a factor used in calculating the correction to the output of a process controller based on the error signal.

Span: the length between successive drive components in a material handling process.

Speed draw setting: a control factor used to compensate for differences in process requirements in different portions of a material handling process. The speed draw setting is used to offset the speed of a process section from a master speed reference.

Tension set point: the desired material tension in a material handling process.

Tuning calculation: a calculation to determine a value for a gain.

Analog value: a factor analogous to a parameter. The analog value may be derived from direct measurement of the parameter or may be derived from a reference related to the parameter. The value may be exactly equal to the actual value of the parameter or otherwise analogous to the actual value of the parameter.

Velocity analog value: a factor analogous to the speed of the material in a material handling process. The analog value may be derived from direct measurement of the velocity of the material or may be derived from a master speed reference for the process.

The method of the invention may be practiced in a material handling process having a single driven segment, or multiple driven segments. In a multi segment process, the method may be practiced on a single segment or multiple segments as desired. A process segment is defined as a portion of the process between two drives, an upstream drive and a downstream drive. The upstream drive is the drive unit located at the beginning of a process segment. The downstream drive is the drive located at the end of a process segment.

The method may be used to control the material tension in a segment by controlling the speed of the upstream drive, the downstream drive, or both the upstream and downstream drives. Controlling the tension by adjusting the speed of the upstream drive may require additional adjustments to the speeds of drives further upstream. Additional adjustments may be required for all upstream drives from the controlled process segment upstream drive, to the initial drive of the process.

Increasing the speed of the upstream drive will reduce the tension in the segment. Decreasing the speed of the upstream drive will increase the tension in the segment. Increasing the speed of the downstream drive increases the tension and decreasing the speed of the downstream drive decreases the tension.

The method is described controlling the tension in a paper web during the process of converting the web from parent rolls to finished products. One of skill in the art understands that the method is not limited to this use and is applicable to any process wherein a continuous material is processed under tension.

According to FIG. 1, the tension in paper web 10 is controlled by the speed difference between the speed of upstream motor 90, and the downstream drive (not shown). This speed difference may be altered by adjusting the output of tension controller 60 to raise or lower the speed of upstream motor 90 via motor controller 80. Raising the speed of the upstream motor 90 relative to the downstream motor (not shown) will reduce the tension of the web 10, and lowering the speed of the upstream motor 90 relative to the downstream process will increase the tension of the web 10.

The output of the controller 60 is adjusted according to the error signal and the gains of the controller 60. The error signal, the proportional gain and the instantaneous integral gain are used in the controller correction calculation to adjust the controller output to reduce the magnitude of the error signal as is known in the art.

The method of the invention determines the instantaneous integral gain of the controller 60 according to the velocity analog value of the web 10 resulting in effective web-tension control over the entire speed range of the web converting process and also accommodates variations in the modulus of elasticity of the web 10, or the wound tension of the web 10.

The method may be practiced using any controller 60 that uses the integral of a value derived from the error signal to derive the controller output correction. An exemplary controller for practicing the method of the invention is a PIC 900 controller available from Giddings & Lewis, Fond du Luc, Wis.

A tension set point, correlated to the desired tension, is determined for the process. The value of the set point is input into the controller. The web tension used to determine the error signal may be measured at any point in the process span where tension is being controlled. Web tension is typically measured by routing the web 10 around a process element attached to a load cell. An exemplary sensor for measuring tension is a Tensioncell 30, available from Comp-trol Inc., Cleveland, Ohio. The error signal is then determined as the difference between the tension set point, and the measured tension.

In one embodiment, the instantaneous integral gain is determined using a maximum integral gain and the web velocity analog value. Maximum integral gain is calculated according to the ratio of the maximum speed of the process and the span of the controlled segment of the process. The maximum integral gain used in the tuning calculation may be based on either the ratio of maximum speed to span length or the reciprocal of the ratio depending upon the specific units of integration used in the controller. The instantaneous integral gain is then varied according to the ratio of the web velocity analog value and the maximum speed set point.

In another embodiment, the instantaneous integral gain is determined according to the web velocity analog value and the span of the process segment without consideration of the maximum process speed or the maximum integral gain. The

instantaneous integral gain used in the controller correction calculation may be based on either the ratio of the web velocity analog value to the process span length or the reciprocal of the ratio depending upon the specific units of integration used in the controller.

The web velocity analog value may be set equal to the master speed reference 20 used to synchronize speeds in the web handling process. Alternatively, the web velocity analog value for a particular segment may be derived from measuring the web velocity in the controlled segment. When the web velocity is measured the analog value may be set equal to the instantaneous value of the web velocity or to a mathematically filtered value of the velocity, to reduce the effects of sudden changes in the velocity. The instantaneous value of the web velocity may be filtered through the use of mathematical smoothing functions as are known in the art.

As the velocity of the web 10 changes, the value of the instantaneous integral gain is recalculated and the controller 60 utilizes the new value of the instantaneous integral gain to determine the correction in the controller output necessary to reduce the tension error value.

Particular controller 60 hardware and/or software may limit the lowest velocity analog value for which an instantaneous integral gain is calculated. The value of the lower limit is determined according to the specific details of the controlled process. In one embodiment the instantaneous integral gain value is fixed at any web velocity analog value less than 1% of the maximum process speed. In another embodiment the integral gain value is fixed at any web velocity analog value less than 0.1% of the maximum process speed. The speed at which the lower limit of the instantaneous integral gain is determined is not limited to the above mentioned embodiments. The lower limit speed may be any speed less than the maximum speed of the process. A lower limit instantaneous integral gain is determined for a selected lower limit web velocity analog value. The lower limit instantaneous integral gain is then used at any web velocity analog value less than or equal to the lower limit web velocity analog value.

Similarly, certain web processing operations may be more reliably executed by selectively applying the use of the instantaneous integral gain in accordance with the details of the web handling process. The use of the integration correction for web tension control may be enabled and disabled depending upon the specific momentary operational parameters of the processing apparatus.

In one embodiment, one or more parameters of the material being processed may be evaluated. The use of the integral control and the instantaneous integral gain may be enabled or disabled based upon this evaluation. A threshold value may be determined for any particular material parameter. A value analogous to the actual value of the material parameter may be determined. For purposes of this discussion, a value analogous to the actual material parameter value is referred to as a material parameter analog value. The use of the integral control and instantaneous integral gain may then be controlled according to the relationship between the determined material parameter threshold value and the material parameter analog value. Controlling the use of the integral control and the instantaneous integral gain according to an evaluation of multiple material parameters may provide a more reliable process control system.

Exemplary material parameters include, without being limiting, material velocity, material tension, material modulus of elasticity, and the quantity of material processed.

Under some operating conditions it may be advantageous to discontinue the use of the integral correction and the

instantaneous integral gain. As an example, the control program may be configured to discontinue the use of the integral correction and the instantaneous integral gain when the web speed drops to zero. Alternatively, the control program may be configured to discontinue the use of the integral control once the web tension falls below a threshold level. In another embodiment, the control program may require that the web velocity fall to zero and that the web tension fall below a threshold value before discontinuing the use of the integral control and the instantaneous integral gain.

The control program may further be configured to subsequently enable the use of the integral control as or after particular conditions are satisfied. Exemplary conditions for enabling the resumption of use of the integral control and the instantaneous integral gain include without being limiting, the web processing speed, the measured web tension, the passage of a predetermined amount of processing time, and the processing of a predetermined amount of web material.

The web processing speed may drop to zero due to a variety of reasons. Downstream faults may cause a momentary stoppage of the web handling process. A web break may cause the stoppage. The web may also stop due to a need to replace the parent supply roll with a fresh roll of web material. The use of the integral control and the instantaneous integral gain may cease as or after the web processing speed drops to zero.

Resuming the use of the integral control and the instantaneous integral gain when the web processing speed rises above zero may be problematic depending upon other operating conditions. If there is slack in the web due to a parent roll change the web tension sensor may not be accurately measuring the web tension. In such circumstances, the use of the integral control and the instantaneous integral gain may result in a "wind-up" effect wherein the tension error accumulates via the integral control and the speed differential between the upstream and downstream drives becomes excessive such that the web snaps abruptly against a web handling element as the last of the web slack is eliminated. The snapping of the web may result in a web breakage.

In one embodiment, the use of the integral control and instantaneous integral gain remains disabled until a threshold level of web tension is sensed. In this embodiment slack in the web is reduced using the proportional gain until a minimum threshold web tension is sensed. Not integrating the web tension error at least until the minimum web tension threshold is reached reduces the likelihood of snapping the web. Delaying the use of the integral control and instantaneous integral gain until the slack in the web is reduced lessens the wind-up effect.

In another embodiment, the use of the integral control and instantaneous integral gain is delayed until a minimum web processing speed threshold is reached or exceeded. In this embodiment, the process increases the web speed at least to the threshold limit before the integral control begins to accumulate tension error. Delaying the use of the integral control reduces the magnitude of the correction attempted by the control program due to the integral control and the instantaneous integral gain. This reduction in magnitude reduces the likelihood of snapping the web.

In another embodiment the use of the integral controller and the instantaneous integral gain may be delayed until a predetermined amount of processing time has elapsed. The amount of processing time may be determined according to typical process performance or as a minimum threshold

beyond which the web processing is sufficiently stable to permit the use of the integral controller and instantaneous integral gain.

In another embodiment, the use of the integral control may be delayed until a predetermined amount of web material has been processed. In this embodiment, the amount of material necessary to stabilize the web is determined and the process proceeds without using the integral control until this amount of web material has been processed. As an example, the splice between the web of a previous parent roll and the web of a successive parent roll may be relatively weak compared to non-spliced web portions. The amount of web that must be processed before the splice is downstream may be determined. The process may then be configured to delay the use of the integral control and instantaneous integral gain until this amount of material has been processed and the splice has moved beyond the risk of snapping.

The process controller may be configured to consider these conditions individually or collectively. In one embodiment the controller may resume the use of the integral controller once the web has reached a minimum web speed, once the web tension has reached a minimum threshold, or once a minimum amount of web material has been processed.

In another embodiment the controller may be configured to resume the use of the integral control and the instantaneous integral gain only once the web tension has reached a threshold value. In another embodiment the controller may be configured to resume the use of the integral control and the instantaneous integral gain only once the web has reached or exceeded a minimum web speed value. In another embodiment the controller may be configured to resume the use of the integral control and the instantaneous integral gain only once a predetermined amount of processing time has elapsed. In another embodiment the controller may be configured to resume the use of the integral control and the instantaneous integral gain only once a particular amount of web material has been processed.

In yet another embodiment, the controller may be configured to resume the use of the integral control and the instantaneous integral gain after either the web tension or the web speed reaches a predetermined threshold value. In yet another embodiment, the controller may be configured to resume the use of the integral control and the instantaneous integral gain after either the web tension reaches a predetermined threshold value or after a predetermined amount of web material has been processed. In yet another embodiment, the controller may be configured to resume the use of the integral control and the instantaneous integral gain after either the web speed reaches a predetermined threshold value or after a predetermined amount of web material has been processed.

The exchange of parent rolls may introduce web slack into the process. This slack may cause the measured web tension to be less than the threshold value for resuming the use of the integral control and the instantaneous integral gain. The slack web may become entangled in the web handling apparatus. In certain high speed web handling embodiments it may be advantageous to resume the use of the integral control and instantaneous integral gain as the web speed is increased regardless of the web tension to reduce or eliminate the web slack and to prevent the slack loop from becoming entangled in the web handling apparatus. Relying upon the achievement of a threshold web tension value for resuming the use of the integral control and the instantaneous integral gain may be problematic. The use of only the web tension condition may not reduce the slack web loop quickly enough to prevent web entanglement issues.

Prior art loop control methods utilize the proportional gain as the primary means of tuning the loop. Adjusting the instantaneous integral gain according to changes in the web velocity analog value provides rapidly responding, stable tension control over the full speed range of a process. Unlike the prior art, the method of the invention uses the proportional gain to accommodate changes in process conditions. As an example, the adverse impact on web tension caused by an out-of-round roll of web may be reduced through the adjustment of the proportional gain. The proportional gain may be set to a high value at low speeds and then reduced according to changes in the web speed to reduce the undesirable effects caused by an out-of-round roll of web. In another embodiment, the proportional gain is selected to provide an adequate response across the process speed range and left unchanged.

The method does not preclude the use of the derivative gain to accommodate sudden large changes in the error signal in a process utilizing a PID controller. An auxiliary proportional gain may also be added to the calculations of the controller. The auxiliary proportional gain modifies the output of the control loop to increase the range of control available and/or provides another means of accommodating process changes.

Multi-segmented web handling processes may have process tension requirements that are unique to the respective process segments. As an example, a process for converting parent rolls of a paper web material into finished paper products may comprise a segment to unwind the parent roll, a segment to emboss the web, a segment to print on the web, and a segment to wind the printed and embossed web. Each segment may require different web tensions for optimal performance. The method as set forth above may be used to control such a multi-segmented process. The additional step of incorporating a speed draw setting **70** into the control method of the invention provides for a more refined level of control.

For each segment of the process, a speed draw setting **70** is determined based upon the Operator's assessment of the tension desired for that segment. The speed draw setting **70** is determined for any particular segment tension desired. The speed draw setting **70** adjusts the speed of the segment from the master speed reference **20** to establish a base operating point for the segment tension. The master speed reference **20** is modified according to the speed draw setting **70** to determine a local speed reference for the motor controller **80**. The web tension is then controlled using the method as disclosed above to maintain the segment process tension.

An additional feedback loop may be utilized to calculate the speed draw setting **70** according to the controller correction calculation. In this embodiment, the speed draw setting **70** is recalculated to reduce the controller correction to zero. Recalculating the speed draw setting **70** to reduce the controller correction maintains the output of the controller **60** in a preferred range.

The method of the invention may be used in any process computing an output correction based on the integral of a value derived from the error signal to handle a material under tension. As non-limiting examples, the method may be used in the handling of wire, rope, thread, fiber optic filaments, films, paper webs, metal foils, ribbon, or any other material that is processed under a drawing tension.

All documents cited in the Detailed Description of the Invention are, in relevant part, incorporated herein by reference, the citation of any document is not to be considered as an admission that it is prior art with respect to the present invention.

While particular embodiments of the present invention have been illustrated and described, it would have been

obvious to those skilled in the art that various other changes and modifications can be made without departing from the spirit and scope of the invention. It is therefore intended to cover in the appended claims all such changes and modifications that are within the scope of the invention.

What is claimed is:

1. A method of adjusting an output in a process for handling a material having a velocity analog value, the method comprising the steps of:

- a) determining an error signal;
- b) determining an instantaneous integral gain according to the velocity analog value;
- c) determining a proportional gain;
- d) determining a first material parameter threshold value;
- e) measuring a first material parameter analog value;
- f) controlling the adjustment of a process output according to the instantaneous integral gain according to the relative values of the first material parameter threshold value and the first material parameter analog value, and
- g) adjusting a process output according to the instantaneous integral gain and the proportional gain.

2. The method according to claim 1 further comprising steps of:

- h) determining a second material parameter threshold value;
- i) measuring a second material parameter analog value;
- j) controlling the adjustment of a process output according to the instantaneous integral gain according to the relative values of either the first material parameter threshold value and the first material parameter analog value, or the relative values of the second material parameter threshold value and the second material parameter analog value.

3. The method according to claim 2 wherein the first material parameter comprises material velocity.

4. The method according to claim 2 wherein the first material parameter comprise material tension.

5. The method according to claim 2 wherein the first material parameter comprises a material quantity.

6. The method according to claim 2 wherein the first material parameter comprises material velocity and the second material parameter comprises material tension.

7. The method of claim 1 wherein the error signal comprises a tension error signal.

8. The method of claim 1 wherein the step of determining the instantaneous integral gain according to the velocity analog value further comprises the steps of:

- h) determining a maximum velocity;
- i) determining the integral gain for the maximum velocity;
- j) determining the velocity analog value; and
- k) determining the instantaneous integral gain according to the velocity analog value and the maximum velocity.

9. The method of claim 1 wherein the step of determining the instantaneous integral gain according to the velocity analog value further comprises the steps of:

- h) determining the velocity analog value; and
- i) determining the instantaneous integral gain according to the velocity analog value and a span of the process.

10. The method of claim 1 further comprising the steps of:

- h) determining a lower limit velocity analog value;
- i) determining a lower limit instantaneous integral gain for the lower limit velocity analog value; and
- j) setting the value of the instantaneous integral gain equal to the lower limit instantaneous integral gain if the velocity analog value is less than or equal to the lower limit velocity analog value.

11. A method of controlling a process for handling a material having a velocity analog value, and a tension, the method comprising the steps of:

- a) determining a set point for the tension;
- b) determining a tension analog value;
- c) determining a tension error;
- d) determining the velocity analog value;
- e) determining an instantaneous integral gain according to the velocity analog value;
- f) determining a proportional gain;
- g) determining a first material parameter threshold value;
- h) measuring a first material parameter analog value;
- i) controlling the adjustment of a process output according to the instantaneous integral gain according to the relative values of the first material parameter threshold value and the first material parameter analog value; and
- j) adjusting a process output according to the instantaneous integral gain and the proportional gain.

12. The method according to claim 11 further comprising steps of:

- k) determining a second material parameter threshold value;
- l) measuring a second material parameter analog value;
- m) controlling the adjustment of a process output according to the instantaneous integral gain according to the relative values of either the first material parameter threshold value and the first material parameter analog value, or the relative values of the second material parameter threshold value and the second material parameter analog value.

13. The method according to claim 12 wherein the first material parameter comprises material velocity.

14. The method according to claim 12 wherein the first material parameter comprise material tension.

15. The method according to claim 12 wherein the first material comprises material quantity.

16. The method according to claim 12 wherein the first material parameter comprises material velocity and the second material parameter comprises material tension.

17. The method of claim 11 wherein the step of determining the instantaneous integral gain according to the velocity analog value further comprises the steps of:

- a) determining a maximum velocity;
- b) determining an integral gain for the maximum velocity; and
- c) determining the instantaneous integral gain according to the velocity analog value and the maximum velocity.

18. The method of claim 11 wherein the step of determining the instantaneous integral gain according to the velocity analog value further comprises the step of:

- a) determining the instantaneous integral gain according to the velocity analog value and a span of the process.

19. The method of claim 11, further comprising the steps of:

- h) determining a lower limit velocity analog value;
- i) determining a lower limit instantaneous integral gain for the lower limit velocity analog value; and
- j) setting the value of the instantaneous integral gain equal to the lower limit instantaneous integral gain if the material velocity analog value is less than or equal to the lower limit velocity analog value.

20. The method of claim 11 wherein the material comprises a paper web material.