MULTIPLE TENSION CONTROL USING A NEW APPROACH IN SIGNAL-PROCESSING

by

S. Krebs

Mississauga, Ontario, Canada

ABSTRACT

A new tension control system is described, which allows the simultaneous control of up to four actuators, such as drives, brakes or clutches. It incorporates four speed/torque control modules and three tension control modules and is referred to as Multiple-Tension-Controller (MTC). All modules can be configured individually for different control schemes and can be interconnected to accommodate any type of application due to their formal and universal character. A significant advantage of such a structure is that it allows the sharing of all related process variable values. This is used to decouple the individual controllers in order to improve the overall control behavior of the web machine. This proposed MTC shows how both simple and complex tension control systems can be configured and optimized in a global manner.

NOMENCLATURE

A	Area of the web
$CS_{i,k}$	Configuration coefficient
E	Modulus of elasticity
F_{fk}	Friction at roller k
F_{pk}	Upstream web force at roller k
F_{nk}	Downstream web force at roller k
$L_{k,k-1}$	Length of the web between roller k and preceding roller
M_{mk}	Applied actuator torque at roller k
$M_{\theta}k$	Inertia torque at roller k
r_k	Radius of roller k (or radius of wound roll)
v_k	Velocity of the web at roller k
$x_{i,k}$	Input of control configuration block
y_k	Output of control configuration block
Δv_k	Difference velocity
$\varepsilon_{k,k-1}$	Strain of the web between roller k and preceding roller
θ_k	Momentum of inertia of roller k including drive system

INTRODUCTION

A web is defined as a continuous, thin, and flexible material which is transported under tension through various processes including printing, drying, coating, laminating, etc. prior to being converted to a final product (see reference[1]). The stations where all these processes take place can be viewed as individual dynamic systems, which are coupled through the web. Thus, disturbances of the web tension caused by a particular process can affect the tension in the other processes. The properties of the web as well as the quality of the motion control of each process determine how well disturbances can be absorbed in order to guarantee the desired operation of the web machine. Conventional tension controls only allow adjustment of the tension in a single tension zone. The tension is measured with a load cell and the controller generates a torque demand for the electrical motor of a driven roller. Other systems use dancing rollers to keep the tension at its desired value. In a web machine with multiple tension zones (see Fig. 1), this approach cannot lead to an optimal control behavior, since every single controller has to detect changes in tension and motion from the running web and this information is not shared between neighboring controllers.
The herein described system was designed to overcome this problem. It incorporates four shaft control modules, three tension control modules, two diameter modules used for winders, and one speed reference module, and is referred to as Multiple-Tension-Controller (MTC). All modules can communicate with each other by a user-configured scheme. A torque reference for each actuator is calculated, meaning that each actuator is operated in torque/current mode. This approach has the following advantages for retrofitting existing web machines or in designing new web machines:

any off-the-shelf actuator (AC/DC drive, brake, clutch) can be used as long as it provides a linear relation between the input reference and the output torque.

the values of all system variables and measured variables can be shared inside the MTC and can be used for control optimization, fault handling, and system diagnosis.

Control parameters which need to be adapted according to different web material properties can be handled consistently.

Appropriate start-up-schemes can be defined according to the web machine application.

The hardware of the MTC is based on a modern Digital Signal Processor (DSP) with 32-bit Floating-Point Arithmetic. The price for these processors has dropped significantly over the passed two years, making them attractive to an industrial market which has been dominated by microcontrollers. Using Floating-Point Arithmetic for the design of digital controllers reduces development times significantly and results in an easier to understand program code [4]. Modern control methods based on time-discrete theories can be implemented by taking advantage of the large dynamic range of the float variables and the performance of the DSP architecture (see Reference [5]).
The four shaft control modules which are implemented in the MTC are identical and can be configured either for winder operation or for transport roll operation (see Fig. 2). All common controller compensation techniques such as friction compensation, load compensation and inertia compensation are built-in. The gain of the speed controller can be adapted to the change of the momentum of inertia which is available as an internally computed value. The three tension control modules are also identical and provide either a torque or a difference velocity signal to be further processed in the connected shaft control modules. Different winding characteristics for different web materials can be adjusted in each module. The reference speed module generates a master speed signal. The diameter modules either output a measured value of the

roll diameter or calculate the diameter using velocity and angular speed information available for a particular roller.

The new approach allows the configuration of an individual tension control system according to the topology of the target web machine. All modules can be interconnected as determined by the application. Closed-loop tension control schemes as well as open-loop tension control schemes can be configured. In cases where more than four actuators are required for a particular application, multiple MTCs can be connected together and can share all information required for the overall process control. A system state controller (SSC) controls the interaction between the different modules during states such as start, tension built-up, normal operation, synchronous operation and stop. The SSC automatically adjusts to the topology of the application, provides a smooth machine operation and initiates appropriate fault handling.

MODELING THE TENSION ZONE

According to Fig. 1 a tension zone is defined as the web path between two consecutive driven rollers. Ideally, the driven roller should completely decouple the input tension from the output tension. However, due to imperfections in the mechanical elements and the control system, undesired transient or harmonic tension variations will be distributed throughout the web machine. A description of the dynamics of a tension zone consists of an equation which describes the dynamic system of the roller with actuator and of an equation which describes the tension in the web.

The dynamics of the k-th roller which is driven by an actuator can be described by summing all forces which are applied to the roller

$$\frac{M_{\Theta k}}{r_k} = \frac{\Theta_k}{{r_k}^2} \cdot \frac{dv_k}{dt} = \frac{M_{mk}}{r_k} - F_{fk} - F_{pk} + F_{nk} \tag{1}$$

In case of a constant velocity of the web, the left side of Eq. (1) equals zero, meaning that the torque developed by the actuator is used for the compensation of the friction losses F_{fk} and the web forces acting on both sides of the roller. Note, that Eq. (1) assumes that there is no slippage between the web and the roller. Fig. 3 illustrates this equation by applying it to each individual roller of the web machine. The following boundary conditions couple the rollers through the web:

$$F_{n2} = F_{p1} \qquad F_{n3} = F_{p2} \qquad \ldots \qquad F_{nk} = F_{pk-1} \tag{2}$$

Considering the law of mass conservation, the tension of the web in between two consecutive driven rollers can be described by the following non-linear differential equation:

$$\frac{d}{dt}\left(\frac{L_{k,k-1}}{1+\varepsilon_{k,k-1}}\right) = \frac{v_{k-1}}{1+\varepsilon_{k-1,k-2}} - \frac{v_k}{1+\varepsilon_{k,k-1}} \tag{3}$$

This equation can be applied for systems with dancing rollers, where a change in tension would result in a change of the length of the web, as well as for systems with tension measurement via load cells. Assuming that the length of the web stays constant which is the case in a system using load cells, Eq. (3) can be simplified by using forces instead of strains which leads to following equation:

$$\frac{dF_{k,k-1}}{dt} = \frac{F_{k,k-1} + E \cdot A}{L_{k,k-1}}\left(v_k - v_{k-1} \cdot \left(\frac{F_{k,k-1} + E \cdot A}{F_{k-1,k-2} + E \cdot A}\right)\right) \tag{4}$$

The result is still a non-linear differential equation which could be linearized in order to carry out further studies of the dynamics of the tension system (see reference [3]). It shows how the web force changes with a change of the velocity of the web. Steady-state operation can be studied by setting the left side of Eq. (4) to zero. With the substitution

$$\Delta v_k = v_k - v_{k-1} \tag{5}$$

an equation for the difference in velocity of two consecutive driven rollers as a function of the difference in web force in the steady state can be found:

$$\Delta v_{k,k-1} = v_{k-1}\left(\frac{F_{k,k-1} - F_{k-1,k-2}}{F_{k-1,k-2} + E \cdot A}\right) \tag{6}$$

Equation (6) shows, how the velocity of the web in a tension zone has to be adjusted relatively to the velocity of the previous tension zone in order to set the desired value of the tension. Thus, a multiple tension controller would generate a difference velocity according to Eq. (6) and use this value together with the velocity of the preceding roller *k-1* as the reference velocity for roller *k*. Equation (6) describes the transfer of tension throughout the different tension zones as the tension in each tension zone depends on the tension of the previous tension zone. The difference velocity is very small, since the term in between the brackets is normally almost zero. An open-loop control of the velocities therefore, either requires a highly accurate drive control or results in acceptable control behavior only for very flexible web materials. Another important condition which needs to be analysed is how the web behaves at start-up while developing tension in a particular tension zone. The input velocity $v_{k-1,}$ is considered to be zero and the leading roller starts to move the web slowly at the velocity v_k. Together with Eq. (4) the following equation can be obtained, which describes the development of tension in a tension zone by controlling the speed v_k of the leading roller:

$$F_{k,k-1} = \int_0^t \frac{F_{k,k-1} + E \cdot A}{L_{k,k-1}} v_k dt \tag{7}$$

According to Eq. (7) the web responds like an integrator acting upon the velocity of the web which is generated by the tension controller. Controlling the tension by using an open-loop control of the velocities near zero speed, instead of a closed-loop control is therefore almost impossible because it requires the knowledge of the initial value of the tension which is stored by the integrator.

STRUCTURE OF THE CONTROL

The objective of the controller design is to find a universal structure, which can accommodate almost any tension control application. As already described in the introduction, different types of control modules can be interconnected in order to be configured for the application. Tension is transferred through the different tension zones by the driven rollers which are all controlled by the MTC. According to Eqs. (1) and (6), the optimal control of the tension in a particular tension zone requires the knowledge of the velocity and the tension in the upstream and the downstream tension zone. A good tension controller therefore should not only consist of a powerful PID-algorithm but should also allow sharing of all relevant variables throughout the whole web machine. This approach differs from conventional tension control systems, and moves more towards a tension controller network, implying that the whole machine motion control is carried out exclusively by the multiple tension controller.
Fig. 4 shows the structure of a shaft control module. Each shaft control module provides a speed PI-controller, three blocks for friction compensation, inertia compensation, and load compensation and a direct torque input. A reference torque for the actuator is generated by summing the outputs of all blocks. The gain of the PI-controller can be proportionally adapted to the value for the momentum of inertia as calculated by the inertia calculator block. Fig. 5 shows the structure of a tension control module.The tension control modules provide a PID-controller and a block for the calculation of the winding characteristic. By connecting the outputs of the tension control modules with the corresponding inputs of the shaft control modules using the following summation scheme

$$y_{0k} = \sum_{i=0}^{n} CS_{i,0} \cdot x_{i,0} \quad y_1 = \sum_{i=0}^{n} CS_{i,1} \cdot x_{i,1} \quad \dots \quad y_k = \sum_{i=0}^{n} CS_{i,k} \cdot x_{i,k} \tag{8}$$

and by enabling the appropriate function blocks, the control can be optimally configured for the application. Hence, the choice of the coefficients $CS_{i,k}$ of EQ. (8) represents a configuration set for a particular application which controls the signal flow of the actual and reference values for tension, torque, velocity, and either wound roll radius or roller radius throughout the control system. Changes of the machine topology during run-time can be handled since the DSP calculates the whole configuration set given by Eq. (8) in every sampling period.

The following control strategies can be configured:

Closed-loop tension / torque control: The output of the tension PID-controller is used as a direct torque reference for the actuator. Compensation blocks can be used to improve the dynamic behaviour of the control.

Closed-loop tension / speed control: The output of the tension PID-controller is according to Eq. (6) multiplied with the value of the velocity reference for the particular shaft and then added to the input of the corresponding speed PI-controller. This leads to a cascaded control structure with speed control and superimposed tension control. Compensation blocks can be used to improve the dynamic behavior of the control.

Open-loop tension / torque control: The reference value for the tension is multiplied by the radius of the roller or wound roll and then output as torque reference for the actuator. Inertia compensation in particular should be activated in order to obtain acceptable control behaviour.

DESIGN OF THE SYSTEM STATE CONTROLLER (SSC)

During the design of the structure of the MTC which is based on different modules, it was recognized, that control of the various states of operation such as start, tension built-up, normal operation, synchronous operation, and stop is better carried out by a built-in state controller than by an external PLC, since all process values are already available to the control system. Faulty events like web breaks, over loads, etc. can be immediately processed after detection without having a communication overhead. In such a system, an external PLC, if required would only provide global enable signals and process system state signals without intervening in the process control.

Besides the error handling, the smoothness of operation of the web machine is an important issue. Depending on the type of actuators and the type of control used in a particular application, different start-up and stop procedures are required. The SSC determines the appropriate procedure based on the given configuration set. Start-up consists of four consecutively processed states:

> State 1 checks for drives / clutches without tension measurement feedback. The MTC then applies minimum speed for a certain amount of time to develop tension.
>
> State 2 checks for drives / clutches with tension measurement feedback. The MTC then applies minimum speed until the start tension is developed.
>
> State 3 checks for brakes with tension measurement feedback. The MTC then runs the drives / clutches at minimum speed until the start tension in the zone controlled by the brake is detected.
>
> State 4 checks for brakes without tension measurement feedback. The MTC runs the drives / clutches at minimum speed for a certain amount of time to develop tension in the zone.

After having successfully gone through these states, the SSC switches all tension references and limiters from a start value to the operating value and accelerates the web machine to its operating speed.

APPLICATIONS EXAMPLE

Fig. 6 shows measurements using 24 cm wide paper as taken from a narrow web machine with rewind station, transport station and unwind station. The rewind and the transport rollers are driven by DC-drives and the unwind roller is driven by a pneumatic brake. Tension is measured via load cells. The first graph shows how the system runs through the different operating states controlled by the SSC. Beginning in the idle state, the SSC first enables the controllers, then enters the start state, and waits until the start tension of 80 N is developed. After start tension has been detected, the machine accelerates and stays in run mode. Upon the stop command the machine decelerates to stand-still and enters again the idle state. The second graph of Fig. 6 shows the reference web speed and the rotational speed of the rewind motor. The third graph of Fig. 6 shows the actual rewind tension as being processed by the tension PID-controller.

CONCLUSION

A new tension control system is presented in this paper. The system is based on a global view of the functionality of a web machine. It incorporates four shaft control modules and three tension control modules as well as two diameter modules and a speed reference module. The modules can be interconnected in order to optimally accommodate the web machine application. An internal System State Controller (SSC) sets reference values and limiter values in the different states of operation. External PLC functions are therefore reduced to a minimum. Due to its flexibility the new system can be used in the design of new web machines, reducing the control complexity, as well as for retrofitting existing web machines by replacing analog controls.

ACKNOWLEDGMENTS

The author would like to thank Rotoflex International and the Ontario Government for their support of this research.

REFERENCES

Proceedings

1. Good, J.K.,"Preface", Proceedings of the Third International Web Handling Conference. Oklahoma State University, 1996
2. Ries, J.P., "Longitudinal Dynamics of a Winding Zone", Proceedings of the Third International Web Handling Conference. Oklahoma State University, 1996
3. Wolfermann, W., "Tension Control of Webs - A Review of the Problems and Solutions in the Present and Future" Proceedings of the Third International Web Handling Conference. Oklahoma State University, 1996

Books

4. Åström, K.J., Steingrimson, H., "Implementation of a PID Controller on a DSP", Digital Control Applications with the TMS320 Family, Texas Instruments, 1991
5. Isermann, R.,"Digital Control Systems", Springer, Berlin, 1990

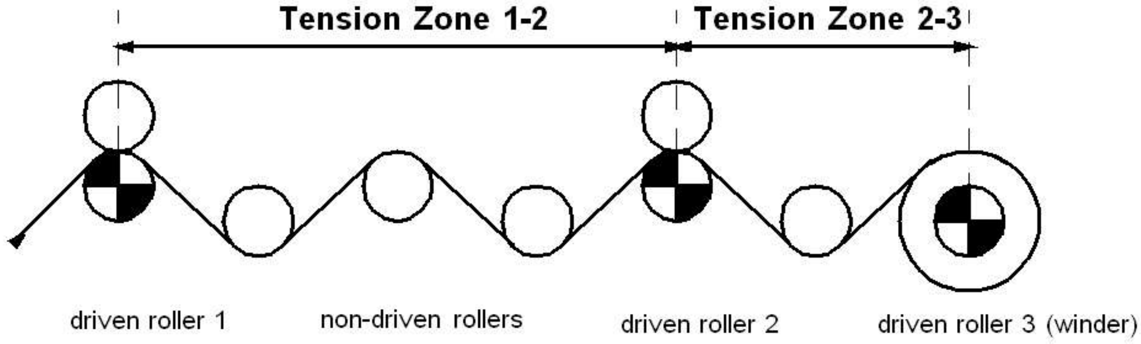

Fig 1: Tension zones in a web machine

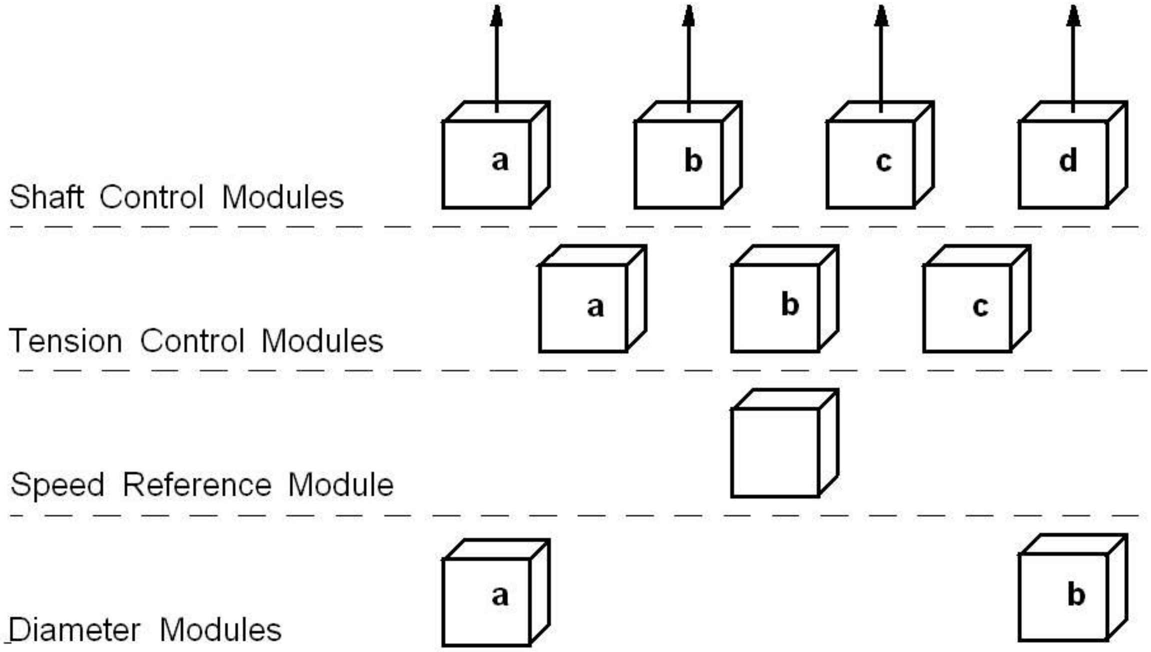

Fig. 2: Structure of the MTC

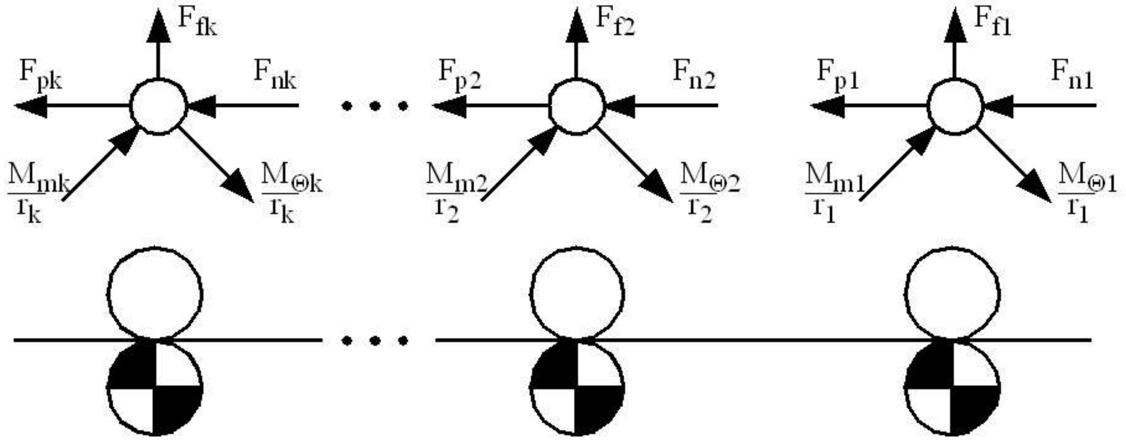

Fig. 3: Forces acting on the rollers along the web path

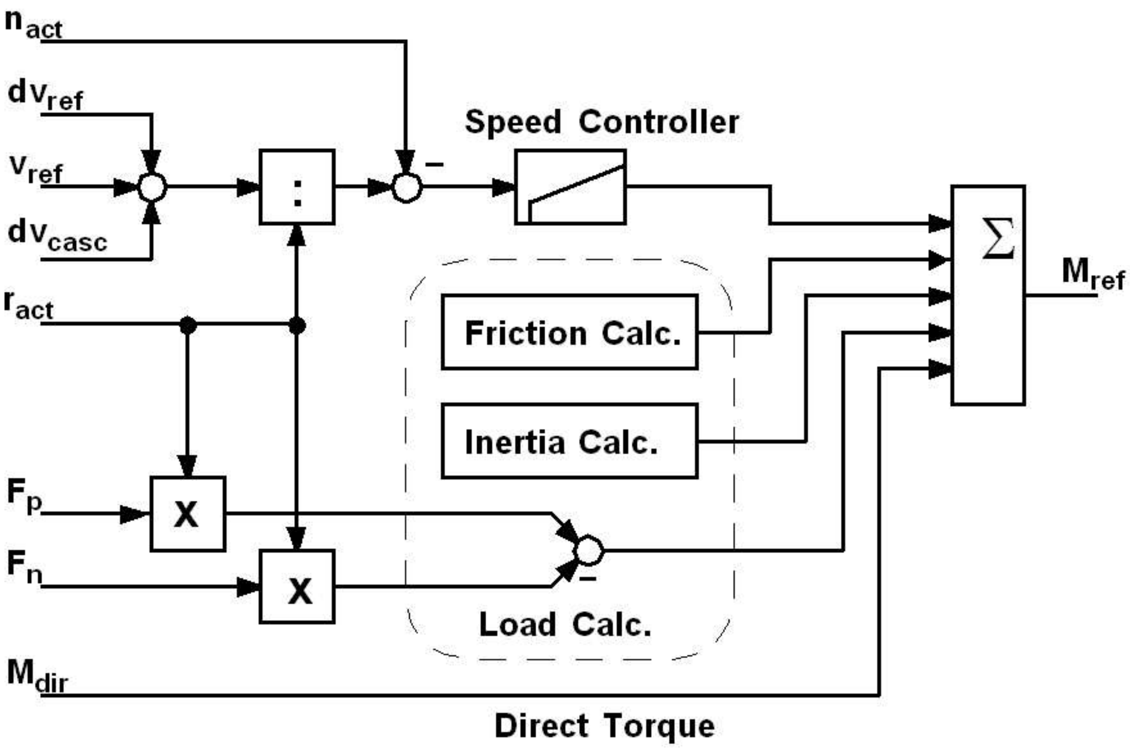

Fig. 4: Structure of a Shaft Control Module

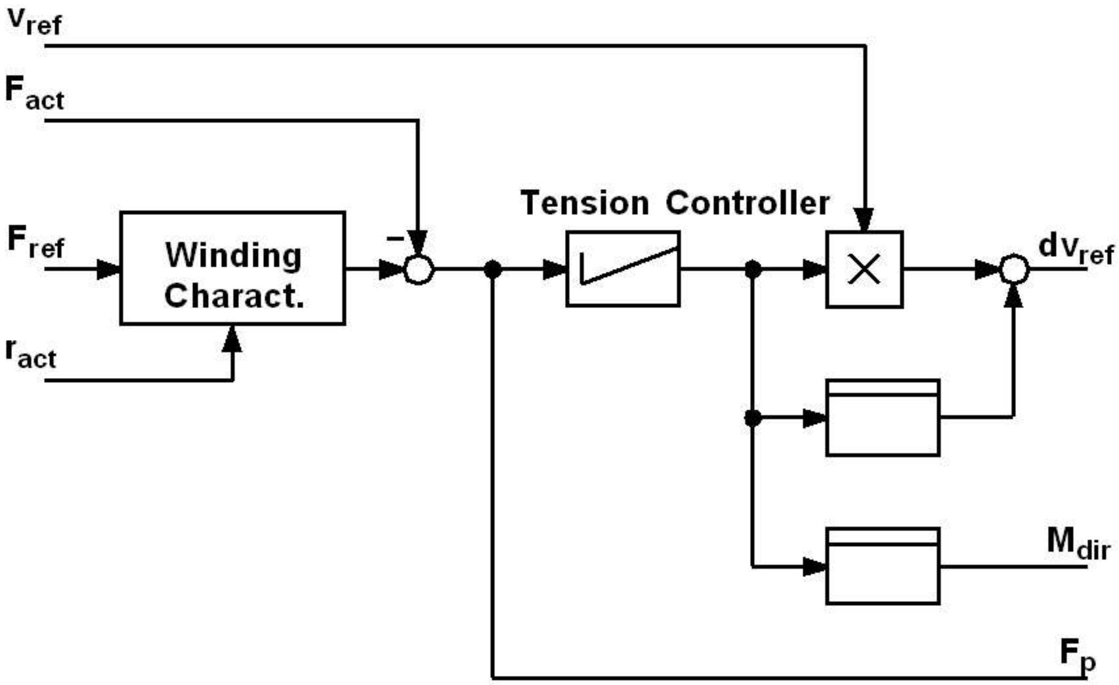

Fig. 5: Structure of a Tension Control Module

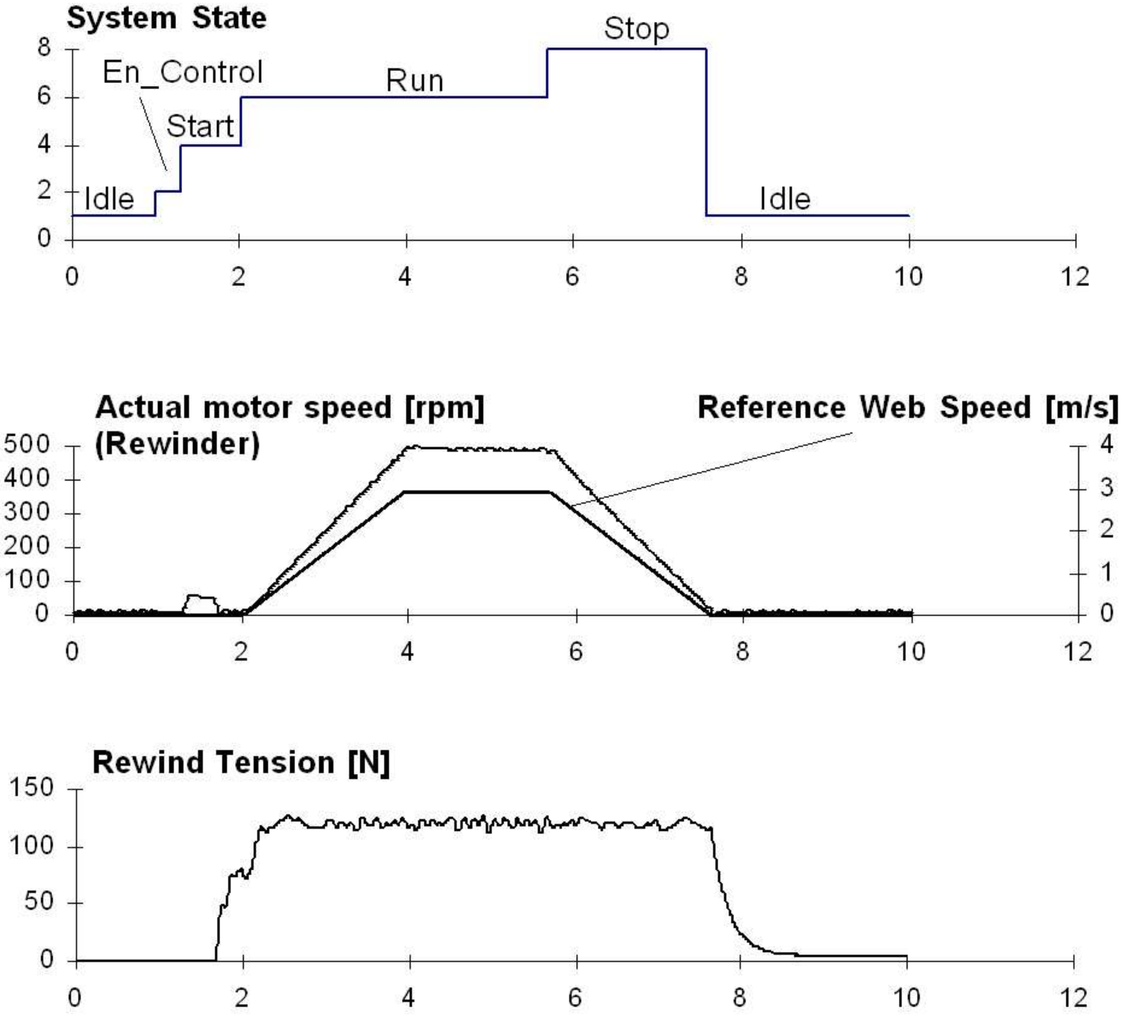

Fig. 6: Measurements taken from a complete operating cycle