Industry 4.0-Focused Dynamic Tension Control in Wet Wipe Production: Development of Automatic Braking and Accumulation System

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Abstract: *In roll-to-roll systems like wet wipe production, the synchronous and smooth unwinding of the web material with constant tension is critical for product quality and production efficiency. Traditional constant belt braking mechanisms cause tension issues due to varying bobbin diameter and friction-induced heating, leading to web undulations, stretching, and breaks in sensitive materials such as wetlace. To overcome these operational challenges, an automatically controlled braking and accumulator system has been developed. The system instantly measures product tension by monitoring web position using a laser ruler and dynamically adjusts the pneumatic brake force via a high-frequency PID algorithm updated every 5 milliseconds. Furthermore, a constant pressure pneumatic piston acts as an accumulator, balancing the web's vertical movements and dampening instantaneous tension variations. This system, compliant with Industry 4.0 principles and based on real-time feedback, solves critical tension control problems, ensures continuity in product quality, and establishes a new concept that is a pioneering example in the global market.*

Keywords: *DYNAMIC TENSION CONTROL, AUTOMATIC BRAKING SYSTEM, WET WIPE PRODUCTION, INDUSTRY 4.0*

1. Introduction

Wet wipe production involves a high-speed, continuous feeding process where achieving stable and precise tension in the raw material web (nonwoven or wetlace) during unwinding is paramount for process stability and product integrity [1]. The efficiency of the roll-to-roll system relies on accurate control of speed, position, and torque, which directly govern web tension [2].

1.1 Challenges in Wet Web Handling

Production lines frequently face challenges during machine start/stop cycles and instantaneous speed variations [3]. These dynamic transitions generate uncontrolled tension fluctuations, resulting in web undulations, stretching, and material breaks.

A. Material Viscoelasticity; The nonwoven and wetlace materials used in this sector exhibit distinct viscoelastic properties, differentiating them from dry paper or film [33, 38]. These materials possess significant internal damping but are also prone to creep and plastic deformation under sustained stress. This makes the tension control problem non-linear; the acceptable tension window is narrow, as over-tensioning causes permanent damage, while under-tensioning leads to wrinkling and steering issues [4].

B. Limitations of Conventional Braking; Existing control systems, typically relying on simple, constant belt braking mechanisms, are insufficient [3]. As the bobbin diameter decreases, the braking pressure must be dynamically reduced to maintain constant torque, a task fixed-mechanisms fail to execute. Furthermore, the resulting excessive friction leads to localized heating, which negatively affects the physical structure and saturation quality of the wet product, further exacerbating material failure [4].

1.2 Research Gaps and Paper Contribution

While extensive research exists on tension control systems using PID and adaptive control [5, 17, 27], a significant gap remains in addressing the combined challenges of: 1) High-frequency disturbance rejection in wet, viscoelastic webs; and 2) Integrating mechanical dampening with dynamic brake control within a single, autonomous Industry 4.0 framework. Previous solutions often relied solely on electrical motor control or simple mechanical dampers without real-time pneumatic actuation [20].

The primary contribution of this study is the development of an automatically controlled braking and accumulator system that uniquely integrates:

Non-Contact Sensing: Real-time, precise tension inference via a laser ruler.

High-Frequency Control: A PID control loop operating at 200 Hz for instantaneous torque adjustment.

Mechanical Filtering: A pneumatically actuated accumulator to isolate the web from transient disturbances.

This integrated approach represents a leap towards autonomous, self-regulating manufacturing systems, fully compliant with Industry 4.0 principles.

1.3 Outline of the Paper

This paper is structured as follows: Section 2 details the System Design and Methodology, focusing on the mathematical justification for the high-frequency control loop and the dynamics of the pneumatic accumulator. Section 3 presents the Results and Discussion, analyzing the system's performance in terms of quality continuity and defect reduction. Section 4 provides the Conclusion and highlights the system's status as a pioneering example in the global wet wipe market.

2. System Design and Methodology

The entire system design is governed by the philosophy of Decentralized Tension Control with Centralized Command, integrating high-frequency sensors, a real-time controller, and dynamic actuators [6]. This approach is mandatory due to the presence of both high-frequency disturbances (mechanical noise, roll eccentricity) and low-frequency transients (speed changes, diameter reduction), which necessitate two distinct control mechanisms: active actuation (Brake Control) and mechanical filtering (Accumulator) [20].

2.1 Dynamic Brake Control Unit (Tension Regulation)

The Control Unit utilizes a cascade control architecture, ensuring stability by continuously compensating for changes in roll diameter, inertia, and pneumatic actuation non-linearities [8, 9].

2.1.1 Real-Time Tension Measurement via Non-Contact Sensing

Web tension is inferred by monitoring the web's out-of-plane position (δ) using a laser ruler (distance sensor) [10, 11]. The primary motivation for using non-contact sensing is the preservation of the fragile, saturated web material [38].

The relationship between web sag (δ) and tension (T) in a horizontal span under the web's own weight per unit length (w) is often approximated by the catenary equation, although simpler parabolic approximations are used in real-time control:

$$T \cong w L^2 / 8 \delta$$

where L is the span length [25]. The system converts the precise displacement signal (Pweb into a tension feedback signal (ΔT) for the controller. The laser's high sampling frequency is crucial to accurately capture the transient vertical oscillations caused by material eccentricity [30].

2.1.2 High-Frequency Adaptive PID Control

The core of the system is the PID control algorithm, which must compensate for the time-varying inertia (J) of the unwinding roll, where $J(R) \alpha R^4$ [14].

The control signal u(t) sent to the actuator is generated by the standard PID equation:

$$u(t) = Kp \cdot e(t) + Ki \int e(t)\, dt + Kd \{ de(t) \} / \{dt\}$$

Adaptive Strategy: Since the roll inertia decreases non-linearly, a fixed-gain PID would lead to instability or sluggish response at different diameters. Therefore, a gain-scheduled or adaptive PID strategy is implemented where the gains (Kp, Ki, Kd) are continuously adjusted as a function of the detected roll diameter or roll inertia [17, 27]. This ensures optimal damping and quick settling times throughout the entire unwinding phase [28].

High-Frequency Execution: The control loop executes at 200 Hz (every 5 milliseconds) [5]. This fast execution rate minimizes the phase lag within the control loop, which is critical for Active

Disturbance Rejection against high-frequency tension ripples and mechanical vibrations [14].

2.1.3 Dynamic Pneumatic Brake Actuation

The PID output is mapped directly to the pressure signal regulating the pneumatic brake force [16].

Actuator Modeling: Pneumatic actuators are subject to non-linearities, including dead zones (minimum pressure required to move the caliper) and hysteresis (dependence on the direction of pressure change) [32].

Linearization: The high-frequency controller incorporates a linearization look-up table and dynamic compensation to ensure that the brake's torque output (Tbrake) is proportional to the command signal from the PID [32]. This meticulous compensation ensures the torque dynamically compensates for the changing radius (R) to maintain constant tension: Tbrake (t) = Tension Setpoint . R(t).

2.2 Pneumatic Accumulator Mechanism (Tension Dampening)

The accumulator mechanism acts as a crucial mechanical filter and tension isolation unit, effectively mitigating the disturbances that the brake system cannot instantaneously suppress [19, 20].

2.2.1 Accumulator Dynamics and Isolation Principle

The accumulator is modeled as a second-order mass-spring system, where the pneumatic piston is the spring element [34].

Ideal Tension Equation: Under idealized low-friction conditions, the web tension (T) is determined solely by the pneumatic piston's load (L):

$$T_{ideal} = L / \{2 \cos(\alpha)\}$$

where 2α is the total wrap angle [35]. The continuous operation under constant pressure guarantees a theoretically fixed output tension [22].

Mechanical Buffer: The mechanism utilizes movable rollers opposed by constant pressure pneumatic pistons [21]. This vertical degree of freedom allows the web path length to dynamically absorb or release length, acting as a mechanical buffer against transient forces [42].

2.2.2 Dampening and Disturbance Frequency Filtering: A correctly tuned accumulator's low mechanical resonance frequency ensures it functions as an effective low-pass filter for tension disturbances originating from the unwinder (upstream) [41, 40]. This prevents the propagation of tension noise to the sensitive downstream sections.

Viscoelastic Compensation: The accumulator provides necessary mechanical compliance to manage the viscoelastic nature of the wet web material. It compensates for stress relaxation and creep by adjusting web length dynamically, preventing the material from reaching its plastic deformation limit during high-stress moments [38].

Control Synergy: The accumulator's position provides a secondary, slower feedback signal to the master line speed control, creating a holistic, stabilizing effect across the entire production line [24].

2.3 Instrumentation, Data Flow, and Safety Interlocks

The system's reliability stems from the synchronization of its digital control units and physical actuators, representing a true Cyber-Physical System (CPS) compliant with Industry 4.0 standards.

Data Acquisition (DAQ): The laser ruler sensor outputs its high-frequency position data (analog or digital) to the main Programmable Logic Controller (PLC) or a dedicated Motion Controller [26].

Control Loop Execution: The PID calculation (200 Hz) executes within the motion controller. The output signal (typically 4-20 mA or digital pulse) is sent to the proportional pressure regulator valve that controls the brake.

Actuation Loop: The proportional valve converts the electrical command signal into a precise pneumatic pressure signal, driving the brake calipers. The fast response time of the valve is critical to avoid introducing further phase lag into the 5 ms control loop.

Safety Interlocks: The system includes safety interlocks that monitor both maximum tension (via the laser sensor) and minimum accumulator position. If the accumulator reaches its limit (indicating potential web exhaustion or excessive slack), the system automatically triggers an immediate, controlled line stop to prevent catastrophic web breaks or machine damage.

Schematic views of the developed system, the accumulation system, and the braking system are presented in Figure 1, Figure 2, and Figure 3, respectively

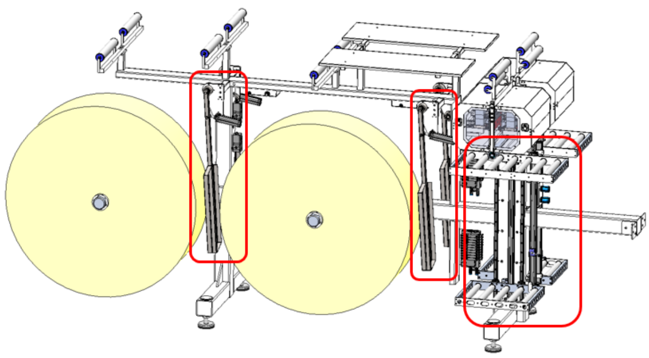

Figure 1. Schematic view of the developed system

Figure 2. The accumulation system

Figure 3. The braking system

3. Results and Discussion

The integrated automatic controlled braking and accumulator system yielded substantial improvements in quality and operational efficiency.

3.1 Continuous Product Quality and Defect Minimization

The system demonstrated superior tension stability compared to fixed systems, eliminating the need for operator input:

Defect Reduction: By maintaining continuous tension stability, the system minimized web undulations, stretching, and achieved a significant reduction in material breaks and production errors across all web materials, including wetlace.

Thermal Control: Elimination of continuous mechanical friction heating solved the problem of heat-induced product damage.

3.2 Industry 4.0 Compliance and Technological Advancement

The project successfully delivered a fully automatic and digitally controlled solution, achieving compliance with Industry 4.0 standards.

Autonomous Operation: The high-frequency PID core acts as an autonomous decision-making mechanism, ensuring consistent performance.

Efficiency Gains: The reduction in friction heating improved energy efficiency, and the elimination of breaks minimized raw material waste (scrap).

Market Leadership: The combination of control precision and high automation established the system as a pioneering example in the global market, validating the benefits of advanced control methodologies.

4. Conclusion

This study successfully developed and validated an integrated automatic braking and pneumatic accumulator system to solve dynamic tension control issues in high-speed wet wipe production.

The system's core novelty lies in its 5-millisecond responsive PID control, which dynamically modulates the pneumatic brake, coupled with a piston-based accumulator mechanism that mechanically dampens transients. This Industry 4.0-compliant solution guarantees continuous and stable web tension, irrespective of machine speed or bobbin size variations.

The project validates that the application of high-frequency sensing and control methodologies can fundamentally solve endemic web handling problems, enhancing the technological competitiveness and operational reliability of modern continuous manufacturing processes.

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