Tension Control for Winding Systems With Two-Degrees-of-Freedom H_∞ Controllers

Dominique Knittel, Edouard Laroche, *Member, IEEE*, Daniel Gigan, and Hakan Koç

***Abstract*—In web transport systems, the main concern is to control independently speed and tension in spite of perturbations such as radius variations and changes of setting point. Multivariable controllers including gain scheduling have already given good results in that sence. Nevertheless, in these control techniques, tracking properties and perturbation rejection are interdependent and cannot be specified separately. In this paper, we present multivariable H_∞ robust control with two degrees of freedom (2DOF) and gain scheduling applied to winding systems. Three controller structures are considered: a global controller, a semidecentralized controller, and a semidecentralized controller with overlapping. Simulation results are given, based on a nonlinear model identified on an experimental bench. In each case, the 2DOF controller is compared to the classical 1DOF controller. The 2DOF approach allows improving significantly disturbance rejection while reducing coupling between tension and velocity.**

***Index Terms*—Control, decentralized control, H_∞, large-scale systems, overlapping control, two degrees of freedom, web transport, winding systems.**

I. Introduction

SYSTEMS transporting paper, metal, polymers, or fabric are very common in industry. The web, coming from the unwinder, is carried along through different treatments before being rolled. As the web tension must be maintained around a rated value, web speed is to be increased as much as possible. Due to disturbance sources (such as noncircularity, radius variations of the rollers, sliding of the web) and to the coupling introduced by the elastic web, the control issue is rather complicated, especially if the system includes many actuators. Generally, proportional–integral–derivative (PID), fuzzy logic, and neural approaches are used [1]–[3]. Recently, multivariable control strategies have been proposed for industrial metal transport systems [4], [5], and for elastic web with H_∞ robust controller [6]–[8].

Paper MSDAD-A 02–29, presented at the 2001 Industry Applications Society Annual Meeting, Chicago, IL, September 30–October 5, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Industrial Automation and Control Committee of the IEEE Industry Applications Society. Manuscript submitted for review October 15, 2002 and released for publication November 15, 2002. This work was supported by the French Ministry of Research through the Project "Winding and high velocity handling of flexible webs" (ERT 8, Contract 01 B 0395).

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Digital Object Identifier 10.1109/TIA.2002.807231

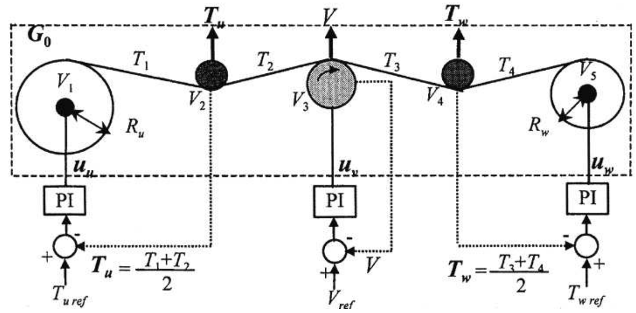

Fig. 1. Distributed control for winding process.

In classical control methods, disturbance rejection and tracking properties are interdependent. To allow independent specifications on disturbance rejection and tracking, a two-degrees-of-freedom (2DOF) controller must be used. In this paper, a 2DOF H_∞ controller design method, based on H_∞ optimization, is proposed for controlling speed and tension of winding systems. This method is evaluated for three controller structures: a global controller, a semidecentralized controller where the system is split into small blocks and a semidecentralized overlapped controller. In each case, comparisons between classical approach and 2DOF are given.

The models used for simulations were validated on a three-motor setup (see the Appendix). Section II gives the development of the models and estimation of their parameters. The nonlinear model is dedicated to the bench simulation whereas the linearized model is used for controller design. Gain scheduling, a technique providing robustness to radius variations, can be used in adjunction with any controller. It is presented in Section III. The global 2DOF H_∞ controller is developed in Section IV; the decentralized 2DOF H_∞ controller in Section V and the semidecentralized overlapping 2DOF H_∞ controller in Section VI.

II. Plant Modeling

A scheme of a three-motor setup with PID controllers is represented in Fig. 1. System G_0 (defined by the dashed box) inputs are torque reference signals (u_u, u_v, u_w) of the brushless motors; its measurements are web tensions T_u and T_w and web velocity V. Web velocity is imposed by master traction motor and web tension is controlled by unwinding and winding motors.

The nonlinear model [7] of a web transport system is built from the equations of web tension behavior between two consecutive rolls and the equations describing the velocity of each roll.

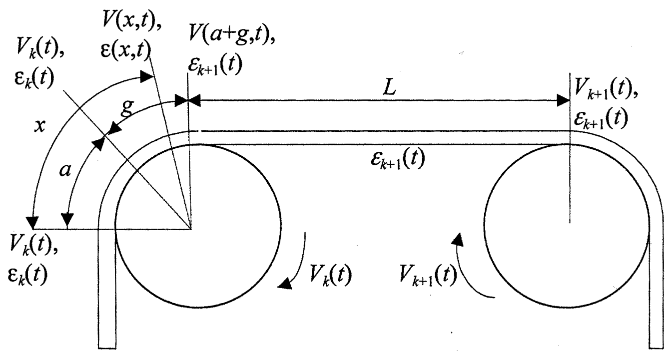

Fig. 2. Web tension on the roll.

A. Web Tension Calculation

Modeling of web transport systems is based on three laws:

- Hooke's law introduces web elasticity;
- Coulomb's law describes web tension variation due to friction and contact between web and roll;
- the law of Conservation of Mass describes coupling between web velocity and web tension.

These laws allow the calculation of web tension between two rolls.

1) *Hooke's Law:* Tension T of an elastic web is function of the web strain ε

$$T = ES\varepsilon = ES\frac{L - L_0}{L_0} \tag{1}$$

where E is Young's elasticity modulus, S is the web section, L is the web length under stress, and L_0 is the web length without stress.

2) *Coulomb's Law:* The study of a web tension on a roll can be considered as a problem of friction between solids [8]. On the roll, the web tension is constant on a sticking zone of arc length g (see Fig. 2).

The web tension between the first contact point of a roll and the first contact point of the following roll is given by

$$\begin{aligned} \varepsilon(x, t) &= \varepsilon_k(t), && \text{if } x \le a \\ &= \varepsilon_k(t)e^{\mu(x-a)}, && \text{if } a \le x \le a+g \\ &= \varepsilon_{k+1}(t), && \text{if } a+g \le x \le L_t \end{aligned} \tag{2}$$

where μ is the friction coefficient, and $L_t = a + g + L$.

Whereas tension varies in the sliding zone, it is uniform in the sticking zone and web velocity is then equal to the roll velocity.

3) *The Law of Conservation of Mass:* is used to develop the tension velocity relation. Let us consider an element of web of length $l = l_0\,(1+\varepsilon)$ and density ρ, under unidirectional stress. The cross section can be assumed constant. According to the Law of Conservation of Mass, the mass of the web remains constant between the state without stress and the state under stress

$$dm = \rho S l = \rho_0 S l_0 \Rightarrow \frac{\rho}{\rho_0} = \frac{1}{1+\varepsilon}. \tag{3}$$

Equation of Continuity [8] applied to the web gives

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V)}{\partial x} = 0. \tag{4}$$

By integrating this relation on variable x from 0 to L_t (cf. Fig. 2), taking into account equation (3), and assuming $a + g \ll L$ (see [10] for details), we get

$$\frac{d}{dt}\left(\frac{L}{1+\varepsilon_{k+1}}\right) = \frac{V_k}{1+\varepsilon_k} - \frac{V_{k+1}}{1+\varepsilon_{k+1}}. \tag{5}$$

This relation can be simplified by deriving the left term and using assumption $\varepsilon \ll 1$

$$L\frac{dT_{k+1}}{dt} = ES(V_{k+1} - V_k) + T_k V_k - T_{k+1}(2V_k - V_{k+1}). \tag{6}$$

B. Web Velocity Calculation

The linear velocity V_k of roll k is obtained from the torque balance

$$\frac{d}{dt}\left(J_k\frac{V_k}{R_k}\right) = R_k(T_k - T_{k-1}) + K_k U_k + C_f \tag{7}$$

where $K_k U_k$ is the motor torque assumed equal to the reference value and C_f is the friction torque. Note that both inertia J_k and radius R_k of unwinder and winder are time dependent and vary substantially during processing.

C. State-Space Representation

The nonlinear state-space model is composed of (6) for the different web sections and (7) for the different rolls. From it, a linear parameter-varying (LPV) model can be deduced by linearization around a setting point. Under the assumptions that J_k/R_k is slowly varying, which is the case for thin webs, V_k can be chosen as state variable in (7), leading to the following linear model:

$$\begin{aligned} E(t)\frac{dX}{dt} &= A(t)X + B(t)U \\ Y &= CX \\ Y &= [T_u \quad V_3 \quad T_w]^T \end{aligned} \tag{8}$$

where $X = [V_1\ T_1\ V_2\ T_2\ V_3\ T_3\ V_4\ T_4\ V_5]^T$ and $U = [u_u\ u_v\ u_w]^T$.

Matrices $A(t)$, $B(t)$, C, $E(t)$ are given in the Appendix.

When frizzing its parameters, the LPV model is converted into a linear time-invariant model that is used for controller synthesis. As the starting phase is the most crucial, the model chosen correspond to this phase, where R_k is maximum for the unwinder and minimum for the winder. However, simulations presented in the sequel rely on the nonlinear equations (1), (5), and (7). The two models both need parameter estimation.

D. Parameter Estimation

Offline identification is based on the model-matching method [11]. The cost function to be minimized is

$$J = \frac{(Y_s - Y_m)^T(Y_s - Y_m)}{Y_m^T Y_m} \tag{9}$$

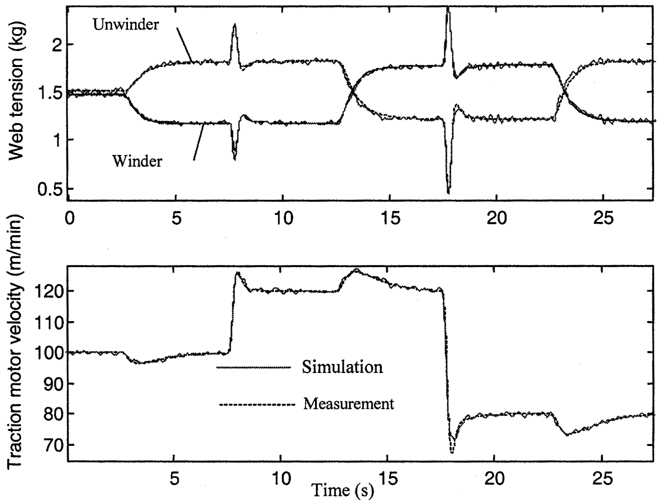

Fig. 3. Identification results with the nonlinear model.

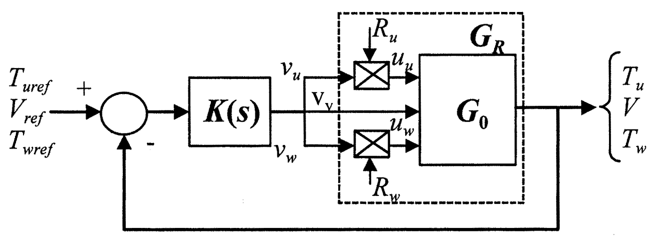

Fig. 4. Modified system.

where Y_s, Y_m are, respectively, the vectors of simulated and measured output signals. Two optimization algorithms are used: the simplex method [12] and the Quasi-Newton method [11]. The simplex method gives the smallest cost function for our application and appears to be more robust to initial conditions. Simulations with optimized parameters and measurements are shown in Fig. 3.

The identified model reproduces the tension and velocity behavior on a wide range of setting point variations.

III. Gain Scheduling Control

Let us consider the unwinder, respectively, the winder, separately. With quasi-static assumption on radius variations, the transfer function between command signal and web tension appears to be inversely proportional to radius [7]

$$\lim_{s\to 0}\frac{T_1(s)}{u_u(s)} \cong \frac{K_u}{R_1} \qquad \lim_{s\to 0}\frac{T_4(s)}{u_w(s)} \cong \frac{K_w}{R_5}. \tag{10}$$

Based on this observation, a new plant G_R is obtained by multiplying the controller output signals v_u and v_w by the radius R_u and R_w, respectively (see Fig. 4). This new plant has the advantage of making the gain at low frequency less dependent on radius and inertia.

Fig. 5 shows the maximum singular values of systems G_0 and G_R at different operating points with different radii (and inertiae).

Gain scheduling improves robustness to radius variations; it is used in control strategies presented in the sequel.

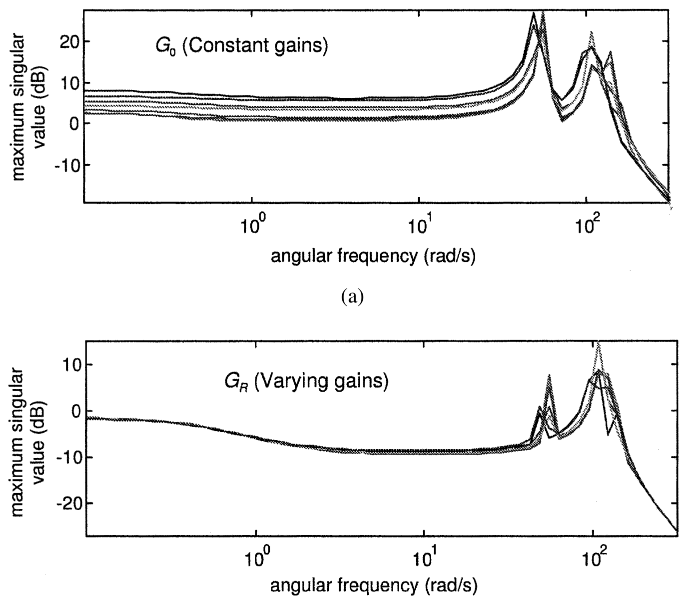

Fig. 5. Influence of gain scheduling on sensitivity to radius. (a) System without gain scheduling. (b) System with gain scheduling.

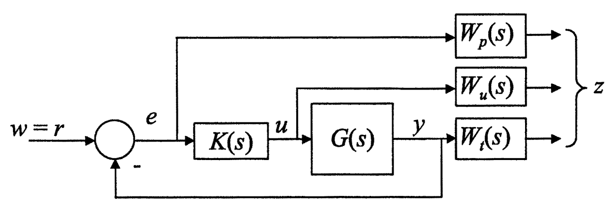

Fig. 6. 1DOF scheme (called S/KS/T scheme).

IV. 2DOF H_∞ Controller

Coupling between web velocity and tension makes the control of web transport systems inherently difficult. Several methods suppressing this coupling in a system with two driven rolls have been studied [13]. For several years, we have developed 1DOF multivariable strategies based on H_∞ and LPV (linear parameter variant) approaches [6]–[8] using mixed sensitivity scheme (Fig. 6). These methods have significantly improved the tracking properties and quasi-suppressed the coupling (Fig. 7).

However, in these methods, disturbance rejections and tracking properties are interdependent. To consider these two issues separately, we have chosen a 2DOF H_∞ control strategy. Typically, the two parts of such a controller $K = [K_f \; K_b]^T$ (Fig. 8) are designed in two steps: disturbances rejection is optimized with K_b and tracking specifications are improved with K_f. However, as we use 2DOF H_∞ method, these two parts of the controller are computed in one step.

In our application, a 2DOF H_∞ controller is designed with output weighting and model matching (Fig. 8). Model M_o is the desired transfer function T_{yr}. Compared to 1DOF strategy, the order of the 2DOF controller is only increased by the order of M_o. In our case, M_o is of order two.

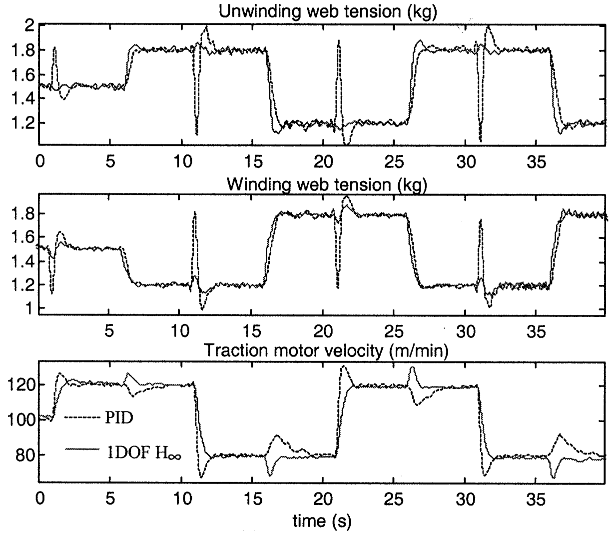

Fig. 7. Comparison PID—1DOF H_∞ (experimental results).

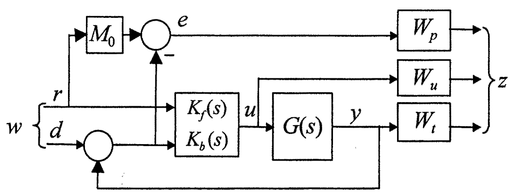

Fig. 8. 2DOF synthesis scheme with output weighting functions and model matching.

The weighting functions W_p, W_u, and W_t appear in the closed-loop transfer matrix

$$T_{zw} := \begin{bmatrix} W_p(M_0 - T_{yr}) & W_p S_e \\ W_u S_u K_f & W_u K_b S_e \\ W_t T_{yr} & W_t T_e \end{bmatrix} \tag{11}$$

where $S_e = (I + GK_b)^{-1}$ is the output sensitivity function, $T_e = I - S_e$ the output complementary sensitivity function, $S_u = (I + K_b G)^{-1}$ the input sensitivity function, and $T_u = I - S_u$ the input complementary sensitivity function.

Controller K is computed using "γ-iteration" (algorithm by Glover and Doyle) [15], in order to minimize the H_∞ norm of transfer function T_{zw} between input vector w (in our case including tension and velocity references r and measurement noises d) and weighted outputs z

$$K = \arg\min \|T_{zw}\|_\infty \tag{12}$$

where $\|T_{zw}\|_\infty = \sup_\omega \sigma_{\max}(T_{zw}(j\omega))$ and $\sigma_{\max}$ denotes the maximum singular value. Let us call γ the achieved value of the optimum. As a consequence of the properties of H_∞ norm, each block of T_{zw} has H_∞ norm inferior to γ. Consider, for instance, $W_p S_e$; the upper right-hand-side block: $\sigma_{\max}(W_p(j\omega)S_e(j\omega)) < \gamma$ for every ω. Weighting functions can adjusted so that γ is inferior and close to 1. Giving high gain to W_p in a band of frequency will provide low gain to S_e. In that sense, frequency response of S_e can be shaped by adequate tuning of W_p. For more information on H_∞ synthesis methods, one may refer to [15]–[17].

In this synthesis scheme, W_p occurs in the two upper blocks of T_{zw}; rejection (S_e) and tracking properties (T_{yr}) then cannot be specified strictly independently. Nevertheless, the model matching technique allows increasing rejection/tracking tradeoff. For more sophisticated schemes allowing independent specification, the reader may refer to [18] and [19].

Weighting function W_p has high gain at low frequencies in order to reject low-frequency disturbances and have the form

$$W_p = \operatorname{diag}\left(\frac{\frac{s}{m} + \omega_{B1}}{s + \varepsilon_0}, \frac{\frac{s}{m} + \omega_{B2}}{s + \varepsilon_0}, \frac{\frac{s}{m} + \omega_{B3}}{s + \varepsilon_0}\right) \tag{13}$$

where m is an upper bound on singular values of transfer functions [20], ω_{Bi} is the required frequency bandwidth, and ε_0 is the steady-state error allowed and must be nonnull as the synthesis method cannot handle pure integrator. We have chosen: $m = 2$, $\varepsilon_0 = 0.01$, $\omega_{B1} = 10$, $\omega_{B2} = 6$, $\omega_{B3} = 10$.

Weighting function W_u is used to avoid large control signals

$$W_u = 0.1 I_{3\times 3}. \tag{14}$$

Weighting function W_t provides roll-off at high frequencies and has the same form

$$W_t = \operatorname{diag}(s,\, 2s,\, s). \tag{15}$$

The order of the resulting controller is 17 (15 for the 1DOF controller). It is then discretized with Tustin method at 10-ms sampling period and can be directly implemented in state-space description. Results are regrouped in Section VI with the results of the following design approaches dedicated to large-scale systems.

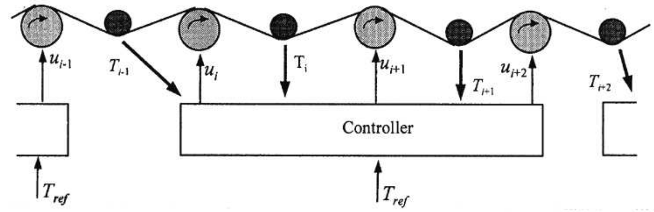

Fig. 9. Semidecentralized control strategy.

V. Semidecentralized Control With 2DOF H_∞ Controllers

In industrial processes including a large number of actuators, it may be inconvenient to use a global multivariable controller. We propose to use semidecentralized controllers, allowing reducing controller dimensions [7]. Validation is made by simulation on a nine-motor plant. The system is split into three parts: each subsystem contains three motors and is controlled independently by its own controller (see Fig. 9).

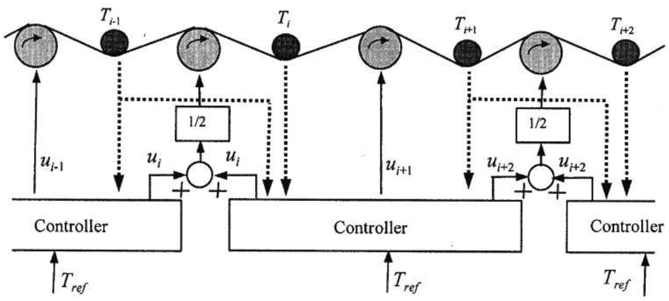

Fig. 10. Semidecentralized overlapped control strategy.

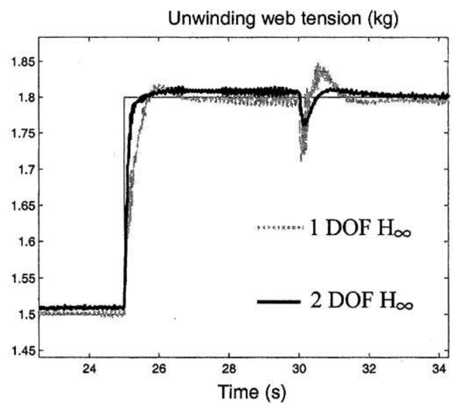

Fig. 11. Comparison 2DOF H_∞—standard H_∞ (simulation).

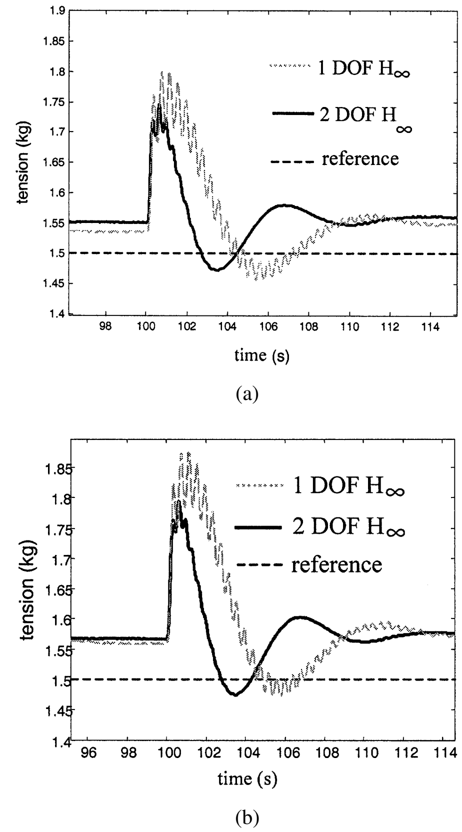

Fig. 12. 1DOF and 2DOF decentralized control without overlapping.

To reduce the coupling existing between two consecutive subsystems, it may be valuable to introduce overlapping [21]; that is, two consecutive controller share some inputs and outputs. For instance, input signals of tractors located at the boundary of two subsystems come from two controllers (see Fig. 10). Such a decentralized overlapping control strategy has already given good results in the case of a vehicle platoon [22].

VI. Simulation Results

Simulations using the nonlinear model have been preceded in order to evaluate improvements due to the 2DOF approach.

A. Three-Motor Centralized Control

In Fig. 11 are shown simulation results with 1DOF and 2DOF centralized controllers for a three-motor bench. The unwinding web tension is first subject to a 20% increase at 25 s; then, a velocity step decrease from 120 to 80 m/min is ordered at 30 s, resulting in web tension changes. The 2DOF controller simultaneously improves tracking and decoupling.

B. Nine-Motor Decentralized Control Without Overlapping

In Fig. 12 are shown simulation results with 1DOF and 2DOF decentralized control without overlapping. As tension reference is constant, equal to 1.5 kg (15 N), a velocity step, from 350 to 450 m/min is ordered at 100 s. Web tensions for two rolls of the central subsystem are represented. We can see that 2DOF significantly reduces tension variations. For both controllers, a 3% static error can be noticed.

C. Nine-Motor Decentralized Control With Overlapping

Simulations have also been carried out in order to compare two decentralized control strategies: 2DOF H_∞ with or without overlapping. The conditions are similar to the previous case with speed change at 80 s. Web tensions in several parts of the web (unwinder and two rolls of the last subsystem) are represented in Fig. 13(a)–(c) during a web velocity increase represented in Fig. 13(d).

We can see that steady-state behavior remains unchanged with several-percent errors whereas the coupling between tension and velocity is substantially reduced with overlapping control. Moreover, the velocity tracking properties are improved.

In Fig. 14 are presented simulation results of the semidecentralized overlapping control with 1DOF and 2DOF. As tension reference is constant, a step variation from 450 to 350 m/min is ordered at 100 s.

Performance is improved, but not as much as in the case of semidecentralized control. Indeed, overlapping already improves decoupling. Nevertheless, one can notice that the tension signal is substantially smoothed, which means that stress on the system is reduced.

VII. Conclusion

Compared to a decentralized PID controller classically used in industry, multivariable H_∞ had already shown good performance in decoupling between speed and tension. When including gain scheduling in order to increase robustness to

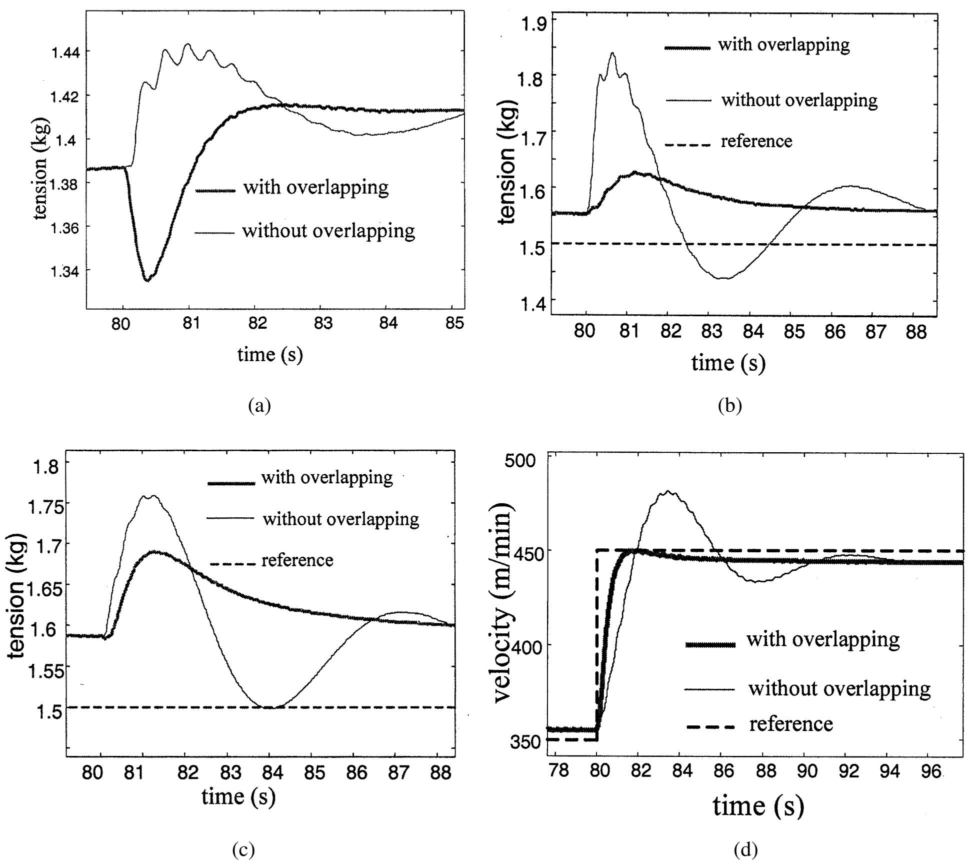

Fig. 13. Decentralized control with and without overlapping. (a) Tension T_1. (b) Tension T_6. (c) Tension T_8. (d) Web velocity.

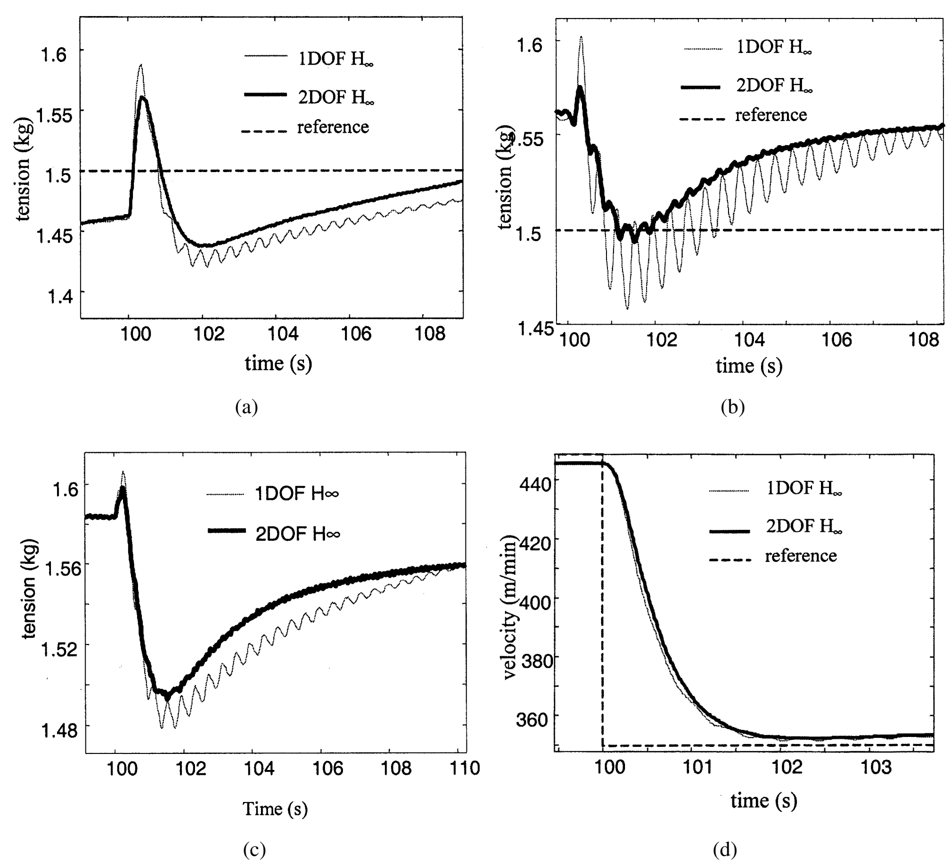

Fig. 14. 1DOF and 2DOF decentralized control with overlapping. (a) Tension T_1. (b) Tension T_6. (c) Tension T_8. (d) Web velocity.

radius variations, the resulting controller had given fine results when implemented on our bench.

The originality of the 2DOF approach is to allow independent specifications on perturbation rejection and tracking properties. When designing the 2DOF controller in one step, as can be done with H_∞ design, the order of the controller is hardly increased, allowing implementation of the 2DOF controller on the same structure as a 1DOF controller. Applying this method on winding systems, we noticed sensible improvements in speed/tension decoupling and tracking properties. These improvements are more important in the case of semidecentralized controllers. Indeed, in this case, coupling between subsystems can be regarded as an output perturbation for a subsystem; decoupling tracking properties and perturbation rejection then appears to be urgent.

Comparison between semidecentralized control with and without overlapping was made and showed that overlapping significantly improves performances. This strategy particularly suits in our case where models are of high order and where the coupling is limited to neighboring state variables of state matrix A.

For simplicity, and in order to make proper comparisons, the weighting functions for 2DOF have been chosen equal to the weighting functions adjusted for 1DOF (except for the global controller). A specific tuning of weighting functions would provide even better performance for 2DOF controllers.

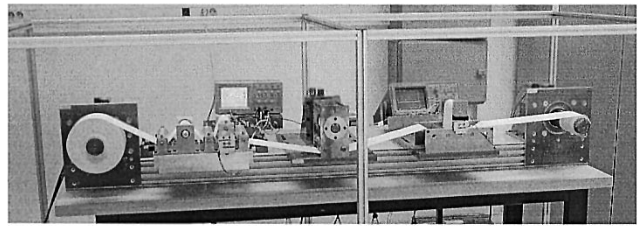

Fig. 15. Experimental setup with three motors and two load cells.

APPENDIX

See matrices $A(t)$, $B(t)$, C, $E(t)$ at the bottom of the page. V_i, R_i, J_i and f_i are the linear velocity, the radius, the inertia and the viscous friction coefficient of the roll i respectively. T_i and L_i are the web tension and the web length between the roll i and the roll $i+1$. K_u, K_t, K_w are the torque constants of each motor. V_0 is the nominal linear web velocity. E_0 is a parameter depending on elasticity modulus E, on web section S and on nominal tension T_0: $E_0 = ES + T_0$. All parameters varying during the winding process are expressed as functions of time. Also, see Fig. 15.

ACKNOWLEDGMENT

The authors wish to thank H. Koç, engineer at Siemens, for his initial investment in the issue.

$$A(t) = \begin{bmatrix} -f_1(t) & R_u^2(t) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -E_0 & -V_0 & E_0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -R_2^2 & -f_2 & R_2^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & V_0 & -E_0 & -V_0 & E_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -R_3^2 & -f_3 & R_3^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & V_0 & -E_0 & -V_0 & E_0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -R_4^2 & -f_4 & R_4^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & V_0 & -E_0 & -V_0 & E_0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -R_w^2(t) & -f_5(t) \end{bmatrix}$$

$$B(t) = \begin{bmatrix} K_u R_u(t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & K_t R_3 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & K_w R_w(t) \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & 0 & \frac{1}{2} & 0 \end{bmatrix}$$

$$E(t) = \mathrm{diag}(J_1(t),\, L_1,\, J_2,\, L_2,\, J_3,\, L_3,\, J_4,\, L_4,\, J_5(t))$$

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