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International Journal on Smart Sensing and Intelligent Systems

ISSN 1178-5608

A GAIN SCHEDULING OF PI CONTROLLERS OF A MULTI-SPAN WEB TRANSPORT SYSTEM

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Submitted: June 2, 2016 ***Accepted: July 31, 2016*** ***Published: Sep. 1, 2016***

Abstract- This research aims to address the issue of controlling a multi-span web transport system by an automatic tuning of the PI controllers parameters. The use of multi-span web transport systems often requires dedicating a particular effort for defining a control system able to protect the integrity of the web. The possibility of using PI controllers for each section is attractive considering that an overlapping system decomposition may permit to take into account the mutual interaction of the neighbor sections. In this case, the choice of correct values of the PI parameters becomes crucial for the control performance. Existing fixed gain PI tension control schemes currently used in industrial practice require extensive tuning and do not provide the desired performance for changing operating conditions. This paper describes a simple strategy for automatically selecting the PI parameters of a multi span transport system by using an nonlinear interpolation of the trend of a preliminary calibration. The algorithm is simple and efficient providing fast real-time implementation, since it does not require any data processing. The proposed technique features robustness and simplicity. The implications of this method reside in its applicability in an industrial platform.

Index terms: Web transport system, Large scale systems, Decentralized control, Overlapping decomposition, Gain scheduling.

I. INTRODUCTION

The business community currently places great demand on product that at some stage of production exist in long flexible sheets, that are usually known as web. Industrial web handling systems are usually composed of a large number of rolls and considered large-scale systems. Those systems are decomposed in subsystems for web tension control and web speed control. All the subsystems have strong interactions with each other and the control of each subsystem is heavily influenced by the interactions with the neighboring ones. In the large-scale systems [1] the control decentralization is necessary because the systems to be controlled are too large and the problems to be solved are numerically too complex and a real time control is not applicable. A solution to the difficulty of the decomposition was introduced since 1998 [2] with a methodology based on a decomposition of the system into subsystems overlapped. The simulation results [2] and some recent experimental tests [3-4] demonstrated that the controller design became easy and that the control performances were better than the conventional decentralized controllers based on a disjoint decomposition and also a PI controller may be adequately used for each subsystem. An important preliminary phase using PI contollers is the opportune tuning of the controller parameters; this operation should be carried out each time that a different reference profile of tension and velocities is requested to the transport platform.

Recently, there are several studies for the fusion of intelligent control techniques to achieve an automatic control parameters tuning for this kind of web transport platforms [5-8]; in [5] a dynamical Bayesian network model has been used, in [6] an adaptive PI control scheme, in [7] $H\infty$ based control, in [8] a self-tuning using adaptive particle swarm optimization (PSO). Sakamoto and Goto [9] proposed a novel structure of neuro-fuzzy decentralized control system, and demonstrated the applicability of this strategy with the PI action to a web transport system by means of computer simulations; recently, in [10] also experimental tests were successfully carried out by using the neuro-fuzzy control.

The present research is aimed to illustrate and to discuss, through extensive experimental data, a simple method for solving the calibration problem by avoiding preliminary time-consuming calibrations every time the user wants to vary web materials, the system setup that change the controlled system dynamics, or the reference profile. In the web transport system, the system dynamics changes so that at the high speeds the system stability is degraded. This paper describes a simple strategy for automatically tuning the PI parameters of a multi-span transport system by using an nonlinear interpolation of the trend of a preliminary campaign of tests in order to estimate the optimal PI parameters in some conditions. The algorithm is simple and efficient providing fast real-time implementation, since it does not require any data processing. Then the proposed algorithm is able to automatically define the parameters for all the conditions on the basis of the initial knowledge opportunely generalized. The system performance is tested on test bench by considering several different setpoints.

The implications of this method reside in its applicability in the industrial platform.

The description of the considered web transport platform, designed and realized for creating a situation similar to a large-scale system with several sections (four main sections) mutually interconnected to each other, is inserted in the section II, the control strategy with the overlapping decomposition is shown in the section III, the analysis of several experimental tests carried out by using an experimental multi-span web transport system, will complete the work in the section IV and discussion. The section V is devoted to conclusions.

II. THE WEB HANDLING SYSTEM

The realized system, already introduced in [12] is composed of four main sections strongly interlaced each other and 12 rolls placed on a mechanical frame at different heights, realized in order to represent a large transport system similar to many industrial ones. The system has been completely renewed at the end of 2015, substituting all the rolls and their bearing with new ones with high performances (low weight and low friction). The new system is depicted in Fig.1 where a scheme of the platform is also depicted: the transport system is driven by 4 servomotors, the first is referred to as the unwinder section, the second to as the lead section, the third to as the draw-roll section, the last to as the winder section (Fig.1). Two couples of tension sensors (one for each side of the web) are placed on the corresponding locations. The first couple of tension sensors is placed after the unwinder roll, and the second one right before the winder roll. The first couple of tensions sensors is followed by the lead section where a couple of guide rolls are wrapped to maximize the contact area between the web and the drive rolls. The control input signals u_i, i=1....4 are sent to the servomotors by using a D/A board. The tension sensors signals feed the A/D board, and the average tension value of the two corresponding sides is considered for measuring the tension after the unwinder (named T_1 in Fig. 1) and before the winder (named T_4). The 4 motor encoder signals (including the speed signals of unwinder section and winder section) feed a digital counter; in the proposed control strategy the velocity of the Lead section (named v_1) and of the Draw-Roll Section (named v_2). The controller's CPU receives signals through A/D boards and counters, performs the control algorithm (C language and Linux operating system), and outputs the command signals in real time to the motor driver through D/A boards.

The whole system is mounted on a mechanical frame, designed for supporting the components of the system, and each of the 4 motors is connected to the respective roller using specific connection joints. The power cables were placed far away with respect to the signal cables and all the cables were covered with insulating tape. Moreover, a set of filtering circuits has been inserted to the analog feedback signal of the tension sensors.

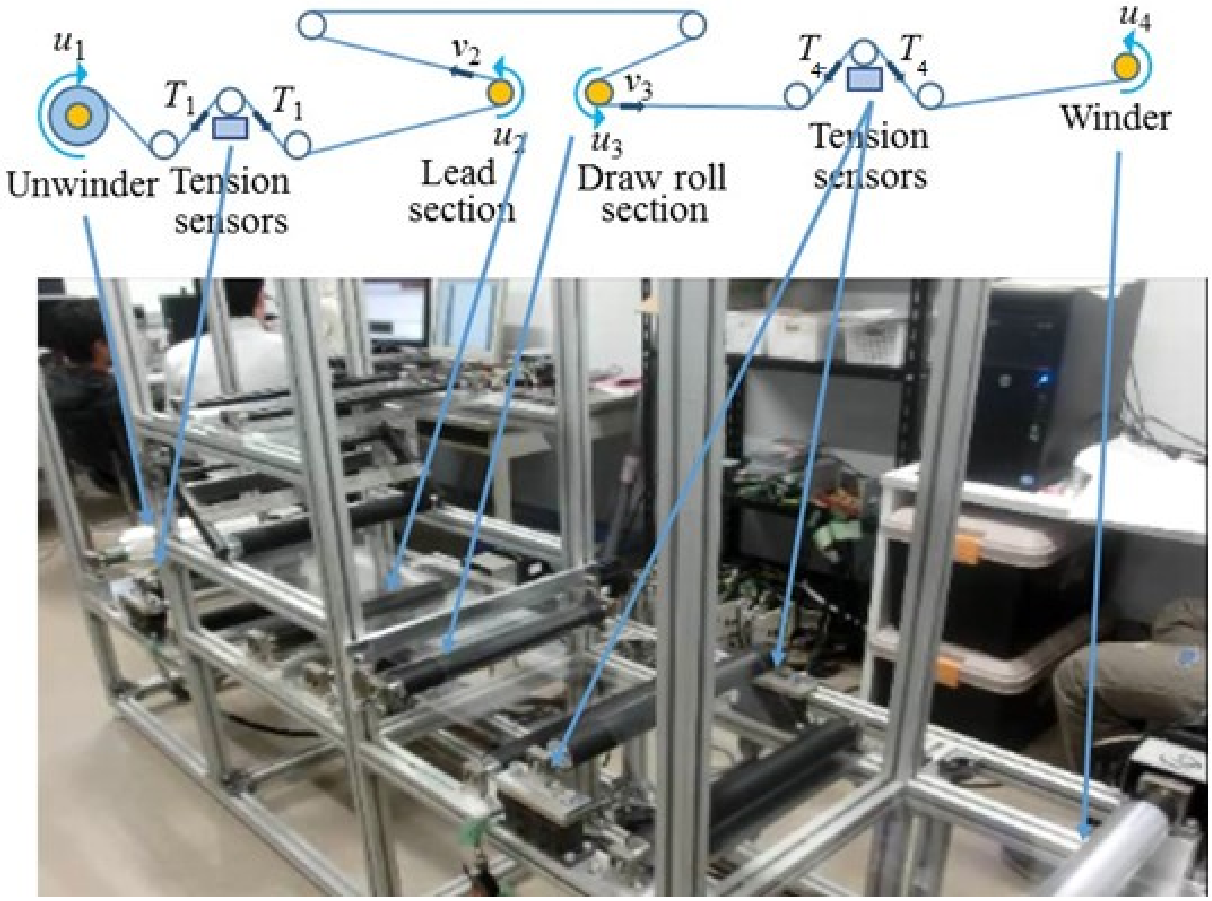

Figure 1. Scheme and photo of the web transport system platform at Kyushu Institute of Technology

The system is constituted by 4 drive rolls that divide the whole system in three sections having length respectively named L_1, L_2 and L_3; the geometrical and mass properties of the 4 drive rolls and of the web film characteristics are shown in Table1.

Table 1: Description of the phisycal properties of the platform.

Web (OPP film)		
Cross-sectional area	A	$1.2\text{x}10^{-6}$(m^{2})
Width		0.3 (m)
Thickness		$40\text{x}10^{-3}$ (m)
Unwinder		
Radius	r_1	$6.5\text{x}10^{-2}$ (m)
Moment of Inertia	J_1	$8.5\ \text{x}10^{-3}$ (kg m^{2})
Span of the section	L_1	0.75 (m)
Leading section		
Radius	r_2	$2.5\text{x}10^{-2}$ (m)
Moment of Inertia	J_2	$1.1\ \text{x}10^{-3}$ (kg m^{2})
Span of the section	L_2	1.2 (m)
Draw roll		
Radius	r_3	$2.5\text{x}10^{-2}$ (m)
Moment of Inertia	J_3	$1.1\ \text{x}10^{-3}$ (kg m^{2})
Span of the section	L_3	1.25 (m)
Winder		
Radius	r_4	$2.6\text{x}10^{-2}$ (m)
Moment of Inertia	J_4	$1.1\ \text{x}10^{-3}$ (kg m^{2})

The linear mathematical model of the web transport systems is based on the relations expressed by the equations applied at each section between two consecutive drive rolls:

-the law of conservation of mass for each web section for evaluating the relation between the speeds of two adjacent drive rolls and the strain ε in the web, (considered constant the length L of the section span between two drive rolls);

- the torque balance equation of the tension forces applied to the sides of the k^{th} drive roll having radius r_k, inertia J_k and angular velocity ω_k;

-the dynamics of the web-material (e.g. Voigt model);

Considering the previous equations, the relation between the tension force T_i applied at the i_{th} drive section of length L_i and the velocity of the neighbour sections v_i and v_{i+1} in the Laplace domain is given by

$$T_i(s) = \frac{P(s)}{L_i}\cdot[v_{i+1}(s) - v_i(s)] \tag{1}$$

$P(s)$ is defined in (2), where , η is the viscosity modulus, $T_v = \eta / E$, E is the elastic modulus.

$$P(s) = A\cdot\eta\cdot[\frac{1+T_v\cdot s}{T_v\cdot s}] \tag{2}$$

A scheme of the system is shown in Fig. 2; in the diagram, a system decomposition of the system is also indicated (dotted line rectangles) introducing the overlapped subsystems 1,2,3 and 4 [12]. The control inputs of subsystems 1 and 4 are torque (indicated as u_1 and u_4 in Fig. 2), while the control inputs of subsystems 2 and 3 are angular speed (u_2 and u_3 in Fig. 2), which means that the speed control mode of the servomotor drive system is used instead of using the torque mode. In the Laplace domain, [12] (3)-(5) express the decomposition in the overlapped subsystems, that may be expressed in a matrix form by introducing the conversion matrix N^{-1} (defined in (6) and the new control inputs vector $\tilde{u} = [\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4]$ tied to the original inputs vector $u = [u_1, u_2, u_3, u_4]$ by (7). Besides, there exists the additional nonlinear dynamics due to the air effects between the drive rolls and web materials, which changes the system dynamics. Thus, if speed references are changed, then the controller parameters should be tuned accordingly to stabilize the system.

$$T_1(s) = \frac{\frac{P(s)}{L_1}}{s + \frac{P(s)\cdot r_1^2}{L_1\cdot J_1}}\cdot[\frac{r_1}{J_1}\cdot u_1(s) + (r_2\cdot s\cdot u_2(s)] \tag{3}$$

$$\begin{aligned} V_2(s) &= r_2\cdot u_2(s) \\ V_3(s) &= r_3\cdot u_3(s) \end{aligned} \tag{4}$$

$$T_4(s) = \frac{\frac{P(s)}{L_3}}{s + \frac{P(s)\cdot r_4^2}{L_3\cdot J_4\cdot s}}\cdot[\frac{r_4}{J_4}\cdot u_4(s) - (r_3\cdot s\cdot u_3(s)] \tag{5}$$

$$N^{-1} = \begin{bmatrix} \frac{r_1}{J_1} & r_2 \cdot s & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -r_3 \cdot s & \frac{r_4}{J_4} \end{bmatrix} \tag{6}$$

$$N^{-1} \cdot U = \widetilde{U} \tag{7}$$

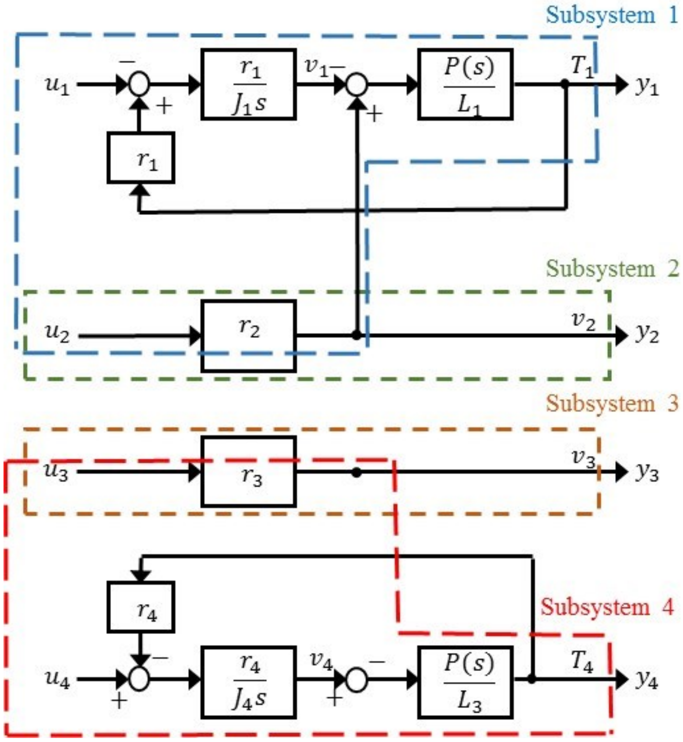

Figure 2. System model scheme with the considered overlapping decomposition

III. CONTROL STRATEGY

a) The control scheme of the overlapped subsystems

For each of the four subsystems individuated with the decomposition previously explained, a classical discrete PI controller (Forward Euler) that has *z*-transform $G_i(z)$ expressed in (8), with k_{pi} and k_{Ii} being the PI parameters of the *i*-th subsystem and T_s the sampling time.

$$G_i(z) = k_{pi} + k_{Ii} \frac{T_s z}{z-1} \tag{8}$$

The use of PI controllers is the most widely used and popular for this kind of systems and it is also considered as a comparison reference when different and more complex controllers are used (i.e. in [6], [8],[10]). A global scheme of the control scheme is shown in Fig. 3 and the matrix *N* (expressed in 9) has been implemented directly on the acquisition board code driving the servomotors.

$$N = \begin{bmatrix} \frac{J_1}{r_1} & \frac{-J_1 \cdot r_2 \cdot s}{r_1} & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{J_4 \cdot r_3 \cdot s}{r_4} & \frac{J_4}{r_4} \end{bmatrix} \tag{9}$$

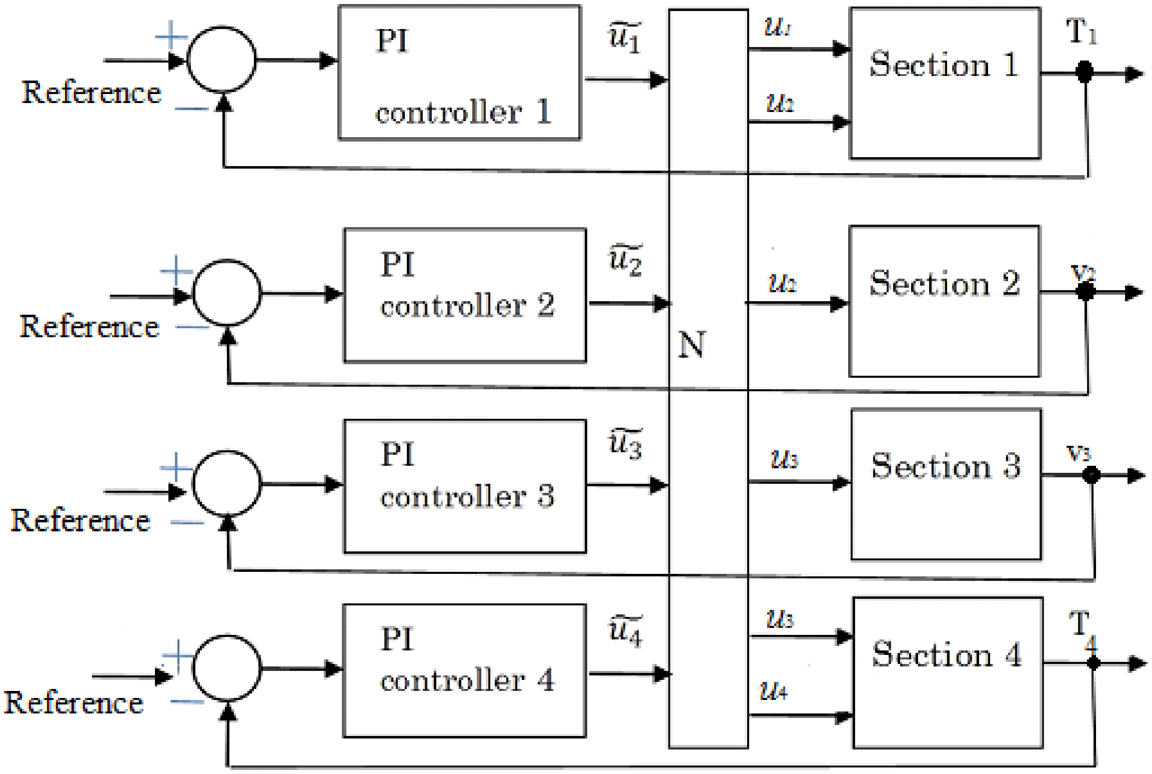

Figure 3. Control scheme of the 4 overlapped subsystems

b) The innovative automatic tuning strategy

An innovative gain scheduling strategy here introduced and proposed is mainly based on the following important assumptions:

- a preliminary testing that permits to build a database of the ''ideal values' of PI parameters to be used in the following experimental phase;

-a different setpoint behaviour for the controlled variables as shown in Fig.4 for a test of 25 seconds. In particular, the first part of the test is referred to the controlled tension forces (variables T_1 and T_4) in such a way that the tension may achieve the target value in the first part the test with velocity setpoint equal to zero (the web does not move). The profile of the tension setpoint on the first 10 second is a smooth first-order curve with a time constant of 2 seconds and it remains constant after 10 seconds. On the countrary, the controlled web velocity (variables v_2 and v_3 in Fig.3) setpoint is blocked at 0 for the first part of the test and then varies to the final value (fixed at 1 m/s for the preliminary testing) with a ramp profile in a time T_m (see Fig.4) that defines the requested rapidity of the system. The value T_m=0 corresponds to the step setpoint. Similarly, the controlled web velocity returns to zero in the same time period T_m (starting from 20 seconds in Fig.4).

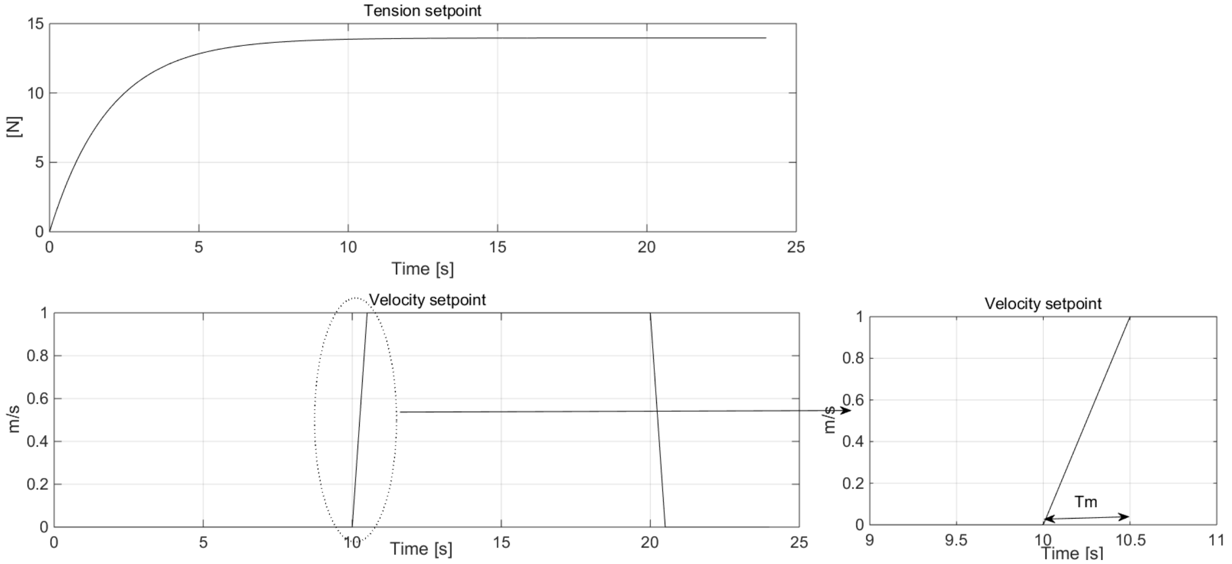

Figure 4. Setpoint assumptions for the proposed strategy

The considered assumptions may be considered reasonable in an industrial situation where it is important that the web transport may start once the desired tension force is achieved on the web.

The preliminary testing has the objective of creating a database of optimum values of the PI controller parameters in relation to the the requested velocity setpoint rapidity expressed by the parameters T_m for achieving, with a ramp profile, the final velocity set at 1 m/s. The database has been created modifying only the parameters k_p and k_I (see eq. 7), with a trial-and-error approach, which is referred to the subsystems 2 and 3 while maintaining the fixed parameters k_p and k_I of the subsystems 1 and 4 and considering a tension final setpoint value of 14 N. Two examples of control used for the database are shown in the experimental test depicted in Figures 5 and 6 (T_m=1 and 2 seconds respectively).

Table 1: Database of PI controller parameters.

T_m [s]	$k_{p2}= k_{p3}$	$k_{I2}= k_{I3}$	k_{p1}	k_{p4}	k_{I1}	k_{I4}
0	0.27	0.03	0.4	0.1	4	1.2
0.33	1.8	0.12	0.4	0.1	4	1.2
0.5	2.7	0.18	0.4	0.1	4	1.2
0.7	2.1	0.15	0.4	0.1	4	1.2
1	2.7	0.18	0.4	0.1	4	1.2
2	1.44	0.09	0.4	0.1	4	1.2
3	2.70	0.18	0.4	0.1	4	1.2
4	3.5	0.24	0.4	0.1	4	1.2

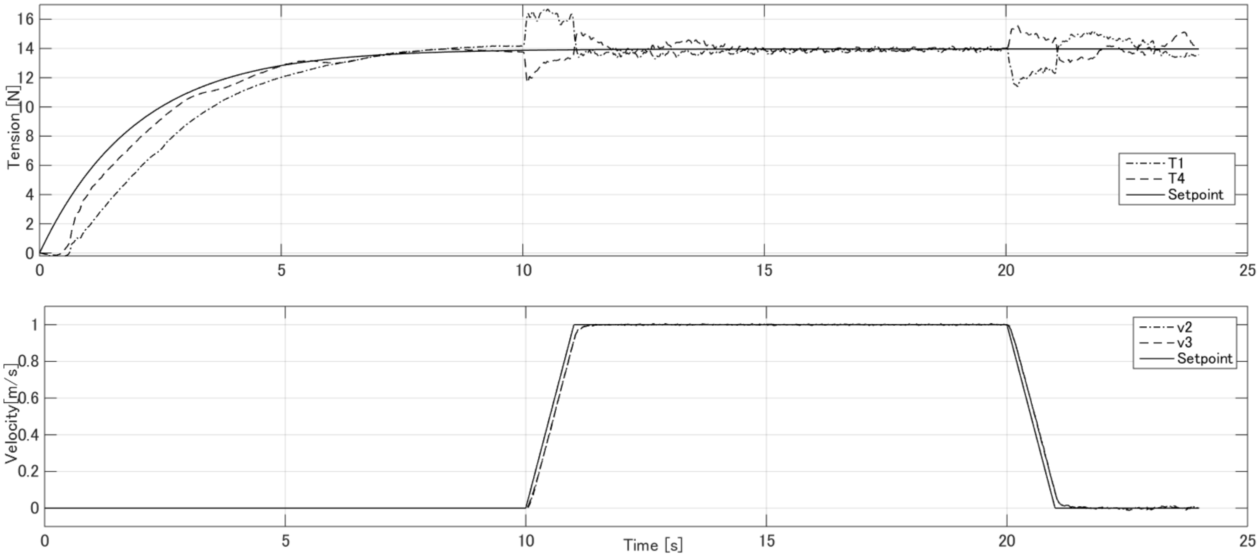

Figure 5. Preliminary experimental tests, T_m= 1 second, kp_2= kp_3=1.7, k_{I2}=k_{I3}=0.18

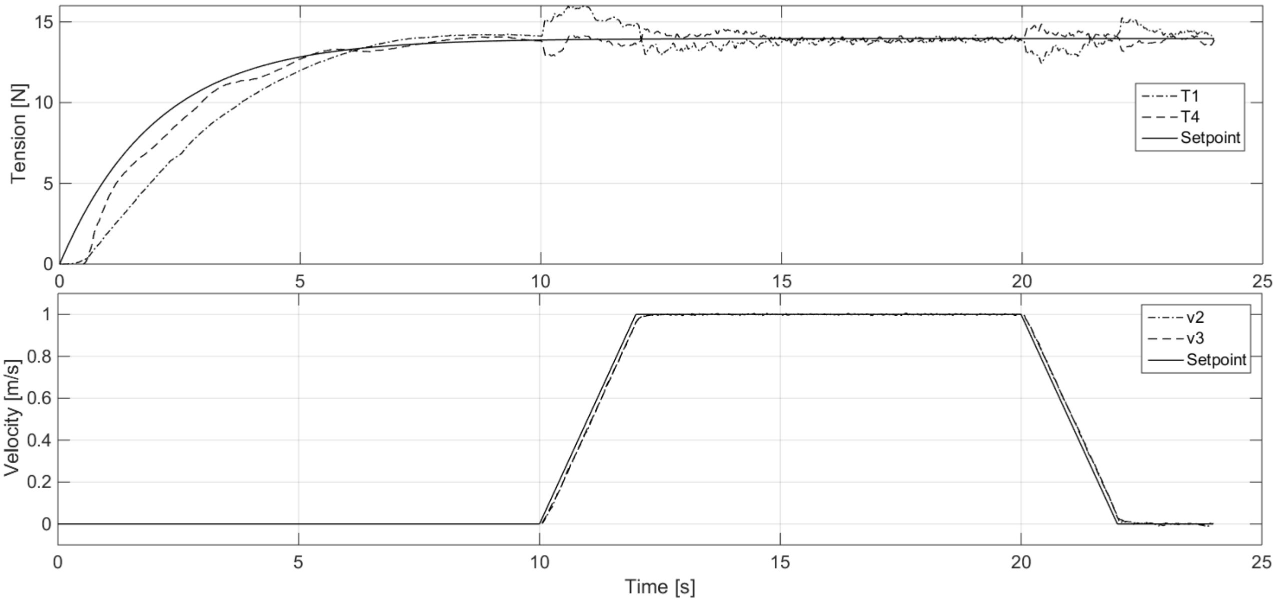

Figure 6. Preliminary experimental tests, T_m= 2 seconds, kp_2= kp_3=1.44, k_{I2}=k_{I3}=0.09

An analysis of the values of optimum parameters k_{p2}=k_{p3} and k_{I2}=k_{I3} shown in the database in Table 1 show a certain nonlinear variation of of the parameters and we choose a nonlinear interpolating equation expressed by Eqs. 10 and 11.

$$k_{p2} = k_{p3} = 3.4(1 - e^{-2.5T_m}) + 0.3 \tag{10}$$

$$k_{I2} = k_{I3} = 0.22(1 - e^{-2.5T_m}) + 0.03 \tag{11}$$

The expressions in (10) and (11) could permit to automatically select the control paramaters for the considered experimental platform, depending only on the velocity, expressed by T_m. The values of the estimated PI parameters for the same T_m values used for the calibration are shown in Table 2; they are sligtly different from the values in Table 1, but this difference doesn’t influence the good control of the web transport platform as it will be shown in the next section.

Finally, it is to be underlined that the proposed interpolating equations tends to converge to constant values when the time of the period T_m becomes greater. It is possible to define (as already evident from Table 2), a threshold value of T_m= 2 seconds that defines a limit over which the control parameters may be considered fixed. This particularity will be investigated in the tests of the next paragraph that will be concerned with the ramp having a duration of at least 2 seconds; anyway this could be considered a reasonably short time for every velocity profile that is necessary to get in industrial applications.

Table 2: PI controller parameters calculated by Eq.(10) and (11).

T_m [s]	$k_{p2}= k_{p3}$	$k_{I2}= k_{I3}$
0	0.3	0.03
0.33	2.21	0.154
0.5	2.94	0.187
0.7	3.28	0.212
1	3.53	0.232
2	3.69	0.249
3	3.70	0.250
4	3.70	0.250

IV. EXPERIMENTATION OF THE AUTOMATIC TUNING PROCEDURE

Several tests have been carried out on the experimental platform for verifying the validity of the proposed strategy. The first group of tests were carried out considering multiple ramp increases of the velocity setpoint automatically controlled by using the Eq. (10) and (11) with the constant tension setpoint of 14 N, the same used for the preliminary database composition.

Some results are shown in Figures 7-9 demonstrating the capacity of the proposed procedure to guarantee an excellent control behaviour achieving the final web velocity of 2 m/s starting from a standstill situation with an automatic PI tuning.

The control results are very good in all the cases by using the automatic tuning: in order to appreciate the slight differences of the different cases, where the setpoint is practically superimposed over the controlled variables values, a zoom of the results in the interesting areas has also been inserted in all the Figures 7-13.

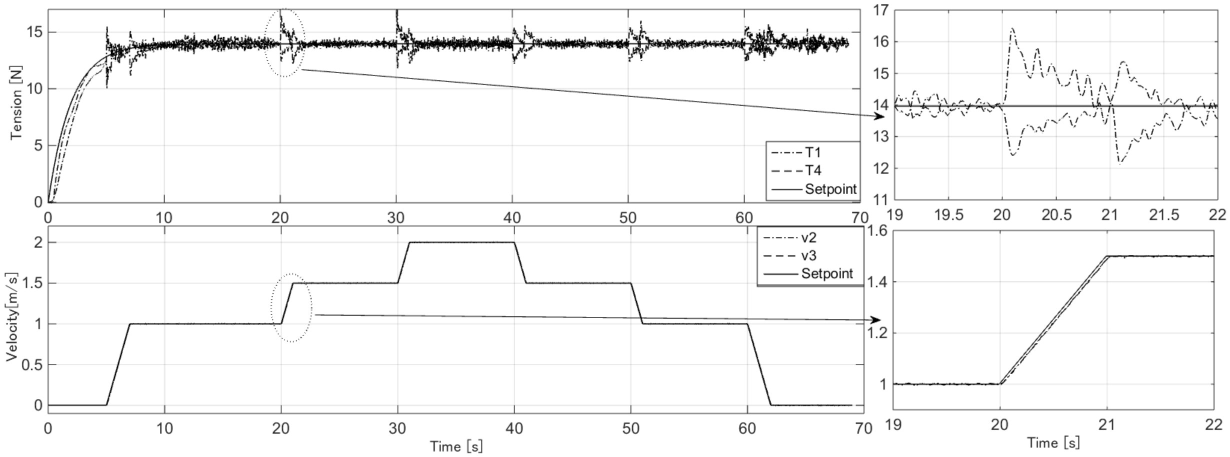

Figure 7. Experimental tests, T_m= 2 seconds, kp_2= kp_3=3.69, k_{I2}=k_{I3}=0.249 (automatic tuning)

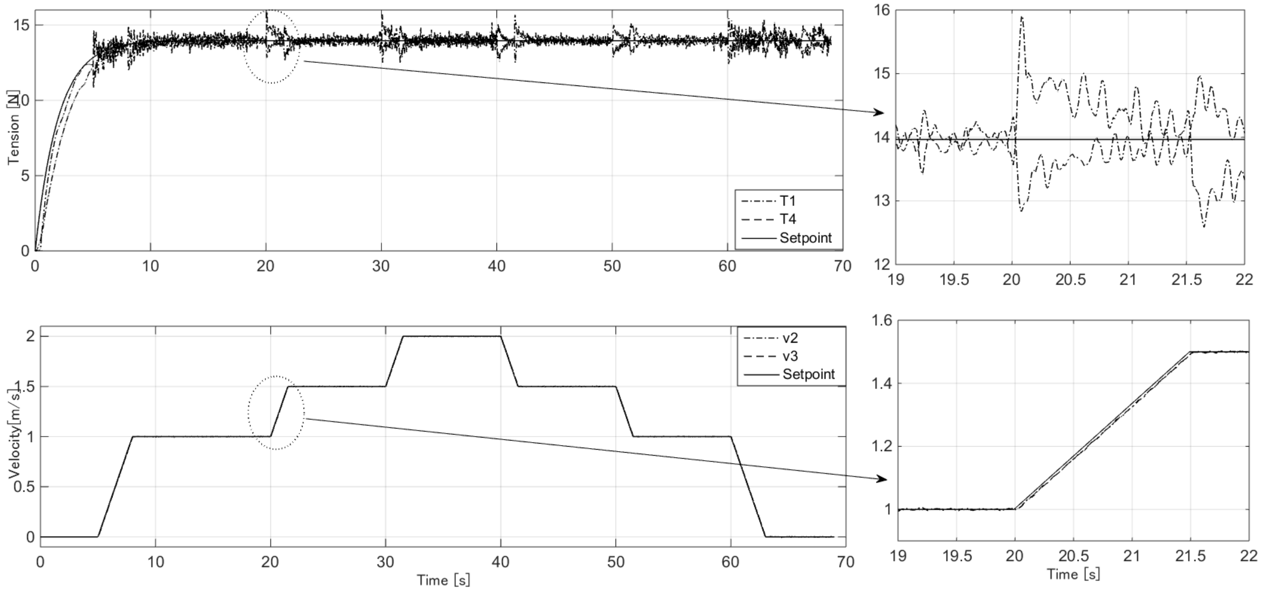

Figure 8. Experimental tests, T_m= 3 seconds, kp_2= kp_3=3.7, k_{I2}=k_{I3}=0.250 (automatic tuning)

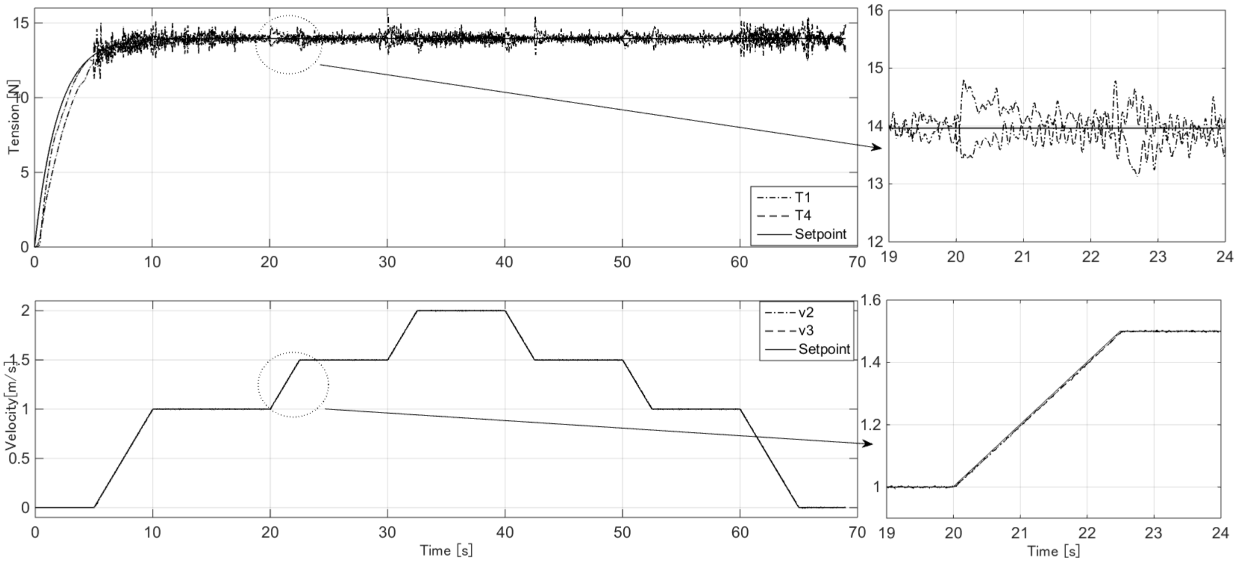

Figure 9. Experimental tests, T_m= 5 seconds, kp_2= kp_3=3.7, k_{I2}=k_{I3}=0.250 (automatic tuning)

a) Testing of the control performances by changing the tension setpoint value

Another task investigated in this research is the robustness of the proposed automatic procedure against a change of the tension force setpoint; this aspect could be interesting in industrial applications where the same platform could be used with different forces requested. At this aim the same Eq. (10) and (11) have been used for checking the performances with a lower tension value [10 N] and an higher tension value [18 N] with a difference of 30% with respect to the value used for constructing the database. In the next Figures 10-13 the excellent experimental control results will be shown, demonstrating the applicability of the automatic procedure also for different tension values.

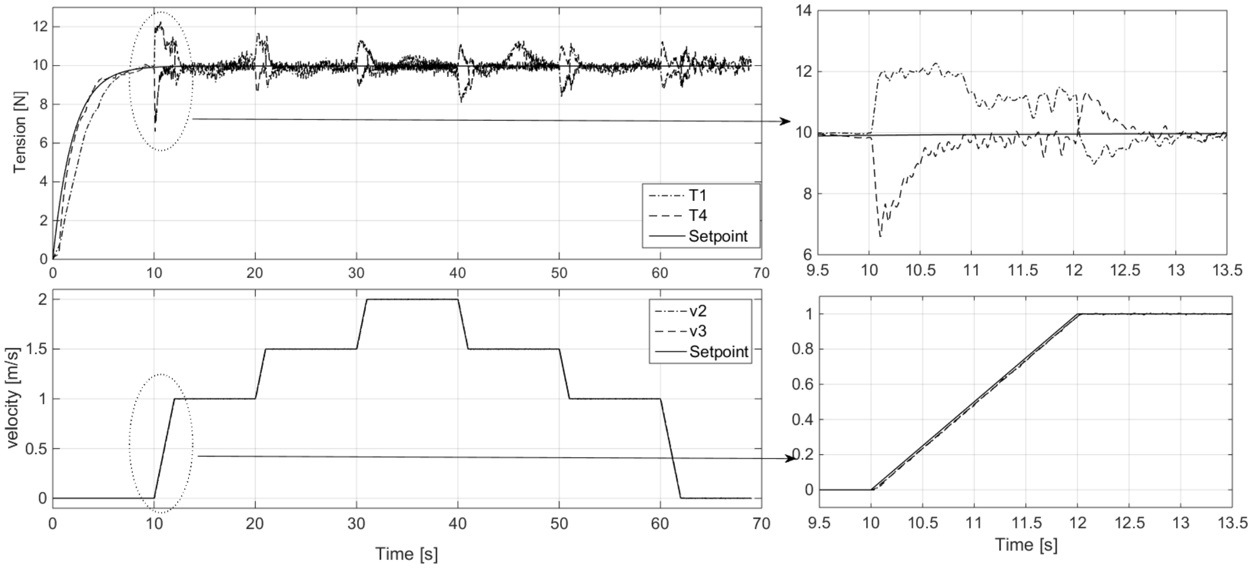

Figure 10. Experimental tests, T_m= 2 seconds, Tension setpoint = 10 N, kp_2= kp_3=3.7, k_{I2}=k_{I3}=0.250 (automatic tuning)

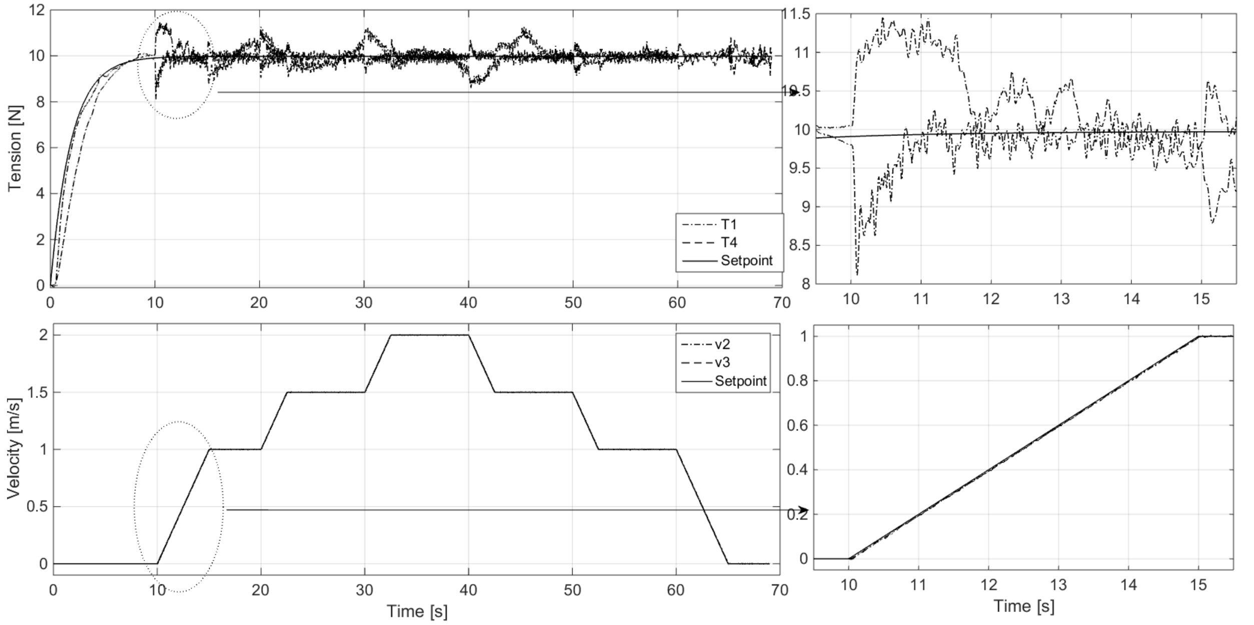

Figure 11. Experimental tests, T_m= 5 seconds, Tension setpoint = 10 N, kp_2= kp_3=3.7, k_{I2}=k_{I3}=0.250 (automatic tuning)

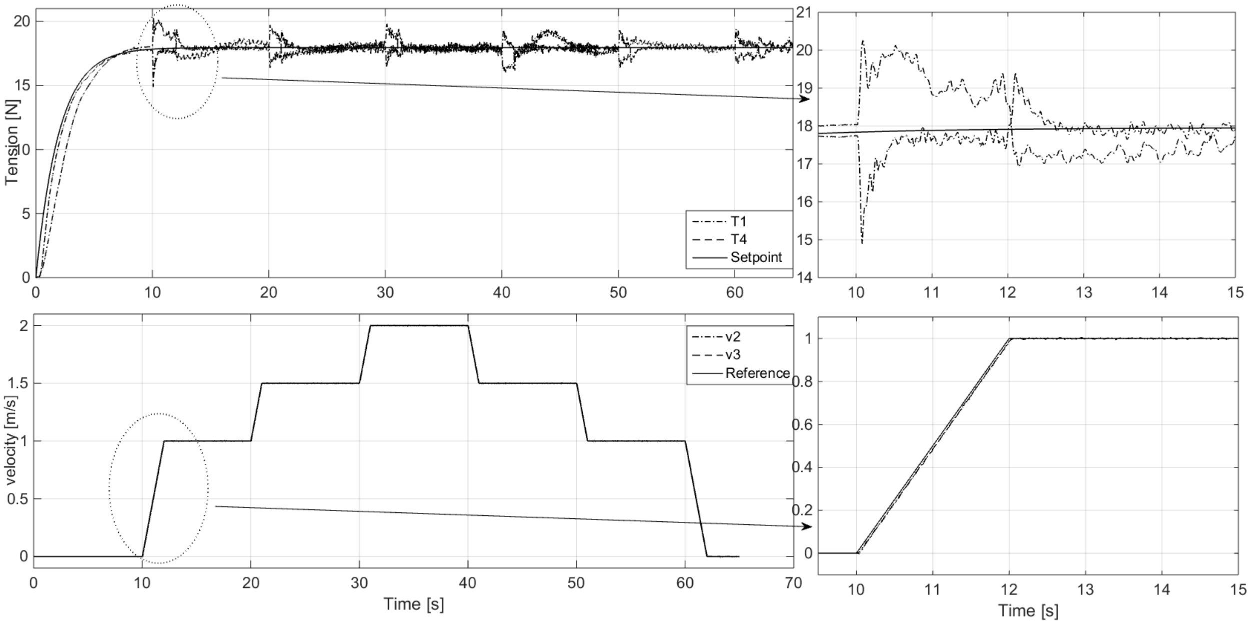

Figure 12. Experimental tests, T_m= 2 seconds, Tension setpoint = 18 N, kp_2= kp_3=3.7, k_{I2}=k_{I3}=0.250 (automatic tuning)

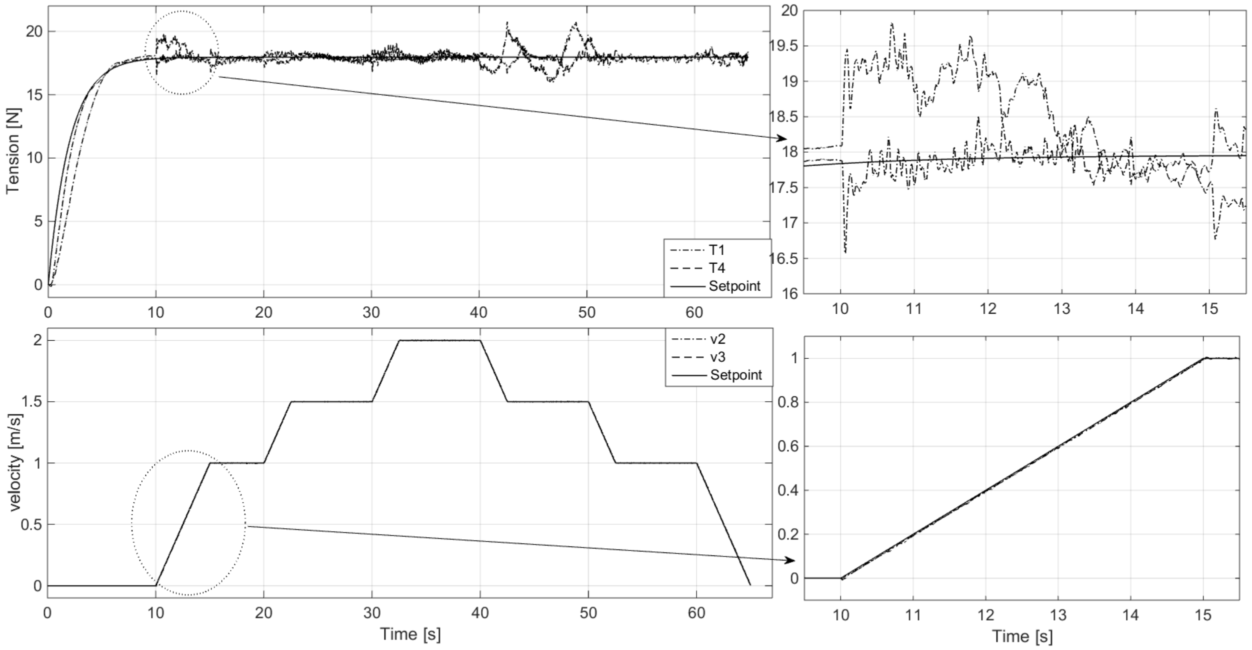

Figure 13. Experimental tests, T_m= 5 seconds, Tension setpoint = 18 N, kp_2= kp_3=3.7, k_{I2}=k_{I3}=0.250 (automatic tuning)

Analyzing the results of Figures 7-13 and considering several conducted tests , it is possible to conclude that the proposed strategy may guarantee an excellent web velocity control from a standstill situation to high speed (2 m/s) by following setpoint ramp profile and also ensuring a good control of the tension forces that never generate uncontrolled dangerous values. The results presented in this paper with the proposed strategy improve considerably the control performances achieved in [3,7].

V. CONCLUSIONS

The importance of testing innovative control strategies for improving the control performance of web handling systems in such a way to guarantee tracking properties and perturbation rejection of web speed and tension is well known, and it is probably of great interest for the industries to successfully run these kind of systems as well.

This paper shows the results of a research that tried to improve the control performance of a multi-span web handling system by automatically tuning the PI parameters used in each section in which the entire control system is decomposed in a form of decentralized structure composed of four drive systems by using an overlapping decomposition.The tuning procedure is based on a preliminary database that permits to generate a curve that connects the velocity PI parameters values determined by the velocity setpoint profile having a ramp shape. The tension force control is localized in the first part of the test while the web maintains motionless.

The experimental results demonstrate the applicability and the advantages of the proposed approach also combining a strategy with an opportune division of the startup of the tension force and velocity variables from the motionless state. Moreover, also a variation of the desired tension force during the web transport is possible by using directly the preliminary database data.

The proposed technique for its simplicity and direct applicability may be very useful expecially on industrial web transport system where the complex procedures could become of difficult application.

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