TECHNOLOGICAL LINE CONTROL VERIFIED ON HIL PLATFORM

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Abstract:
The paper deals with the design and experimental verification of a new control structure with reference model for the tension control in the technological processing line the stability of which is derived on basis of the second Lyapunov method. The properties of the proposed controller were verified by experimental measurement on a new concept of hardware-in-the-loop (HIL) simulation platform based on programmable logic controllers (PLC). The experimental measurements confirmed that the proposed control structure is robust over a wide range of controlled system significant parameters changes together with invariance and desired dynamics prescribed by the reference model.
KEYWORDS: CONTINUOUS LINE, TENSI0ON CONTROL, ROBUST CONTROL, HIL SIMULATION

1 Introduction

Technological processing line represents a multi-motor drive system in which the individual drives are mechanically coupled through the web of material. The tension control quality in this technological line significantly affects the quality of the line final product in many web processing industries (textile, paper, metal, polymer). Web tension control systems can be regarded as a nonlinear multivariable system. Due to the strong coupling between web velocity and web tension during normal operation cycle there exist many sources of disturbances e.g. web sliding, vibrations, change of web-elasticity. These disturbances are transmitted to the web tension that can result in in bad quality or even in the destruction of the material being processed.. For this reason the control strategy for continuous technological lines should be robust with respect to the uncertainties and disturbances [1].

Web tension regulation is a rather challenging industrial control problem. A review of the web tension control problems can be found in [2]. Proportional-integral-derivative (PID) [3, 4], fuzzy logic [5, 6], neural network [7, 8], optimal control [9, 10], and robust control approaches [11, 12] are used. Recently, robust Lyapunov-based feedback control [13, 14] and multivariable $H_{infinity}$ controller with one or two degrees of freedom control strategies have been proposed for industrial web transport systems [15].

Regarding control structure, centralized control structure has many drawbacks and researchers have proposed decentralized control [16-18] and overlapping decentralized control [19] to improve the performance over centralized control structure.

The increasing requirement on tension control performance in technological lines requires the use of more better solutions and sophiticated control approaches. Due to the fact that multi-motor drives occur in practice as parts of larger technological assemblies, it is necessary to look for such methods of their control that would be simply and easily physically interpretable. Otherwise their wide application in industrial practice cannot be expected.

Therefore our aim was to design a simple controller that would ensure the required value of tension in the web independent from its speed. The basic idea of the control method lies in extending the system by a new suitable state variable which represents additional information into the controlled system easily obtained from the system´s output variable. The proposed controller then secures asymptotic stability of the extended system and also zero control deviation based on the application of the Lyapunov synthesis.

The properties of the proposed controller were verified by experimental measurement on a new concept of hardware-in-the-loop (HIL) simulation platform based on generally available hardware (PLC) and software means (MATLAB).

2 Preconditions and means for resolving the problem

2.1 Technological line structure

The middle part of the continuous line is a typical representative of technological line for processing continuous flows of material (e.g. sheet metal strips, tubes, processing lines in paper mills and printing works, etc.) in the field of elastic or plastic deformation, which influences the material´s mechanical properties. Figure 1 shows the structure of the middle part of a continuous line (CL).

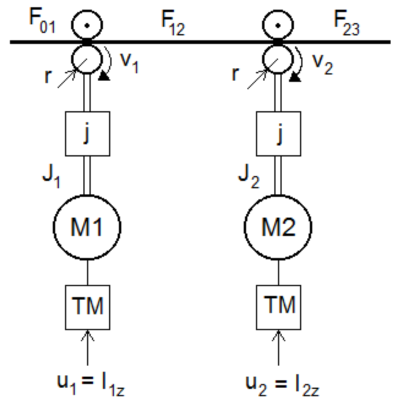

Fig. 1 *Structure diagram of middle section of continuous line*

The legend for the diagram in Fig. 1 is as follows:
F_{01}, F_{23}- tension before 1st machine, tension before 2nd machine,
v_1, v_2 – 1st machine rolls velocity, 2nd machine rolls velocity,
F_{12} – tension between 1st and 2nd machine,
r – roll radius, j – gearbox, M1,M2 – DC motors,
J_1, J_2 – moments of inertia of rolls, TM – static converter,
I_{2z} – desired current value of motor M2,
I_{1z} - desired current value of motor M1.

Assume that the converter has proportional transfer and an integrated subordinated current loop the time constant of which is substantially shorter compared to the time constants of the remaining subsystems of the CL middle section, so it can be ignored.

The block diagram of CL middle section under this (practically real) assumption is shown in Fig. 2. The parameters of the CL model are specified in the Appendix.

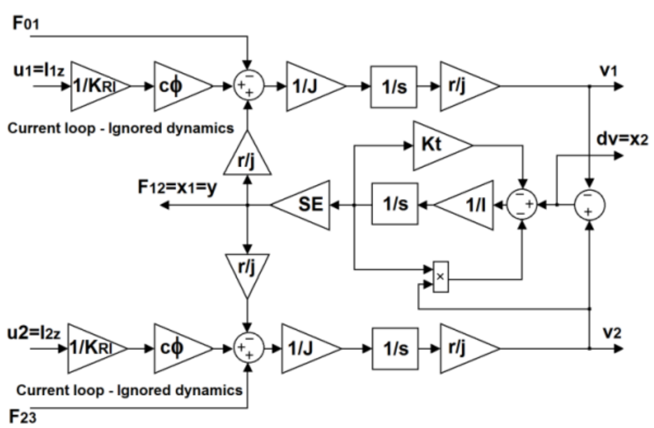

Fig. 2 *Continuous line block diagram*

In terms of control this is a 3rd order MIMO system with two inputs [$u_1=I_{1z}$, $u_2=I_{2z}$] and two outputs [F_{12}; v_2], which can be influenced by two additive disturbances [F_{01}, F_{23}].

2.2 Technological line tension control

The precise tension control is the main goal of control in such systems. The tension should have a constant and non-oscillating course in all operation stages (start-up, deceleration) under consideration the influence of disturbances before and after the section of the line as well as of changes of parameters (e.g. the moment of inertia).

In terms of tension control the controlled system will be a 2nd order system with two inputs [$u_1=I_{1z}$, $u_2=I_{2z}$] and one output $y=F_{12}$. The first state variable will be the tension ($F_{12}=x_1$) and the second state variable is the difference of the circumferential velocities of the rolls ($dv=x_2=v_2-v_1$), where velocity v_2 is considered as an additional disturbance.

The state description of the middle section of the CL in terms of tension control according to Fig. 2 has the form

$$\begin{bmatrix} \frac{\mathrm{d}x_1}{\mathrm{d}t} \\ \frac{\mathrm{d}x_2}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} -\left(\frac{K_t+v_2}{l}\right) & \frac{SE}{l} \\ -\frac{2r^2}{j^2J} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{rc\emptyset}{jJK_{RI}} \end{bmatrix} u_1 +$$

$$+\begin{bmatrix} 0 \\ \frac{F_{01}\,r}{jJ} + \frac{F_{23}\,r}{jJ} + \frac{rc\emptyset}{jJ\,K_{RI}} u_2 \end{bmatrix} \tag{1}$$

The dynamic properties of tension in the middle section of the continuous line will be prescribes by a reference model. As for the 2nd order controlled system we need to obtain additional information on the unknown parametrical and also additive disturbances, we will extend its reference model by one state variable $x_{3M} = x_{eM}$, which will secure that in steady state the tension control disturbance is equal to zero. The reference model will be a 3rd order linear system the dynamics of which can be set according to [20] by a single optional positive parameter α. This reference model can secure optimal dynamical properties of the controlled system in terms of the minimal control disturbance and minimal input power criterion [20]. If we need to settle the tension in the web of material within approximately 1s, then based on the Shannon-Kotelnikov theorem the value of the parameter will be α=5. Then the extended state description of the reference model for the 2nd order system is

$$\begin{bmatrix} \frac{\mathrm{d}x_{eM}}{\mathrm{d}t} \\ \frac{\mathrm{d}x_{1M}}{\mathrm{d}t} \\ \frac{\mathrm{d}x_{2M}}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{\alpha^3}{2} & -\frac{3\alpha^2}{2} & -\frac{3\alpha}{2} \end{bmatrix} \begin{bmatrix} x_{eM} \\ x_{1M} \\ x_{2M} \end{bmatrix} + \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} w \tag{2}$$

Note: The tension is generated by the first drive in opposite direction to the line speed, which is represented by the work rolls circumferential velocity v_2 of the second drive.

The block diagram of the considered reference model is shown in Fig.3.

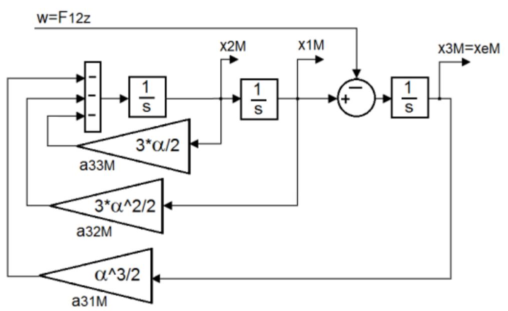

Fig. 3 *Reference model extended by an additional state variable*

It is clear in Fig. 3 that in steady state the input of integrator x_{3M} will equal zero and tension will equal the desired value w.

In terms of CL middle section tension control this is a 2nd order controlled system (eq.1) which similarly to the reference model will be extended by an additional state variable x_e. Its state description is as follows

$$\begin{bmatrix} \frac{\mathrm{d}x_e}{\mathrm{d}t} \\ \frac{\mathrm{d}x_1}{\mathrm{d}t} \\ \frac{\mathrm{d}x_2}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -(\frac{K_t+v_2}{l}) & \frac{SE}{l} & 0 \\ -\frac{2r^2}{j^2J} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_e \\ x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -\frac{rc\emptyset}{jJK_{RI}} \end{bmatrix} u_1 +$$

$$+\begin{bmatrix} 0 \\ 0 \\ \frac{F_{01}\,r}{jJ} + \frac{F_{23}\,r}{jJ} + \frac{rc\emptyset}{jJ\,K_{RI}} u_2 \end{bmatrix} \tag{3}$$

If we establish the reference model and system deviation as

$$\mathbf{e} = \mathbf{x}_{\mathrm{M}} - \mathbf{x} \tag{4}$$

then through simple modifications we will obtain a system whose states are represented by state deviation $\mathbf{e}$

$$\frac{\mathrm{d}\mathbf{e}}{\mathrm{d}t} = \mathbf{A}_{\mathrm{M}}\mathbf{e} + \mathbf{f} - \mathbf{B}u \tag{5}$$

where we have denoted

$$\mathbf{f} = (\mathbf{A}_{\mathrm{M}} - \mathbf{A})\mathbf{x} + \mathbf{B}_{\mathrm{M}}w - \boldsymbol{d} \tag{6}$$

then $\mathbf{f}$ is the generalized disturbance vector which comprises all parametrical and additive disturbances affecting the system with regard to its reference model.

If we choose the Lyapunov function for system (5) as

$$\mathrm{V} = \mathbf{e}^{\mathrm{T}}\mathbf{P}\mathbf{e} = \mathbf{e}^{\mathrm{T}}\mathbf{z} \tag{7}$$

where $\mathbf{z}$ is the weighted state deviation vector

$$\mathbf{z} = \mathbf{P}\mathbf{e} \tag{8}$$

and $\mathbf{P}$ is a positive definite matrix which elements according to [20] have form

$$\mathbf{P} = \begin{bmatrix} \frac{\alpha^5}{2} & \alpha^4 & \frac{\alpha^3}{2} \\ \alpha^4 & \frac{5\alpha^2}{2} & \frac{3\alpha^2}{2} \\ \frac{3\alpha^2}{2} & \frac{3\alpha^2}{2} & \frac{3\alpha}{2} \end{bmatrix} \tag{9}$$

The derivation of Lyapunov function (7) with regard to system (5) while it applies that $\mathbf{Q}$=-$\alpha\mathbf{P}$ is

$$\frac{dV}{dt} = -\mathbf{e}^{\mathrm{T}}\mathbf{Q}\mathbf{e} + 2(\mathbf{f}^{\mathrm{T}}\mathbf{z} + \mathrm{b}_2\mathbf{u}) = -\alpha\mathbf{e}^{\mathrm{T}}\mathbf{P}\mathbf{e} + 2(\mathbf{f}^{\mathrm{T}}\mathbf{z} + \mathrm{b}_2\mathbf{u}) =$$
$$-\alpha\mathbf{e}^{\mathrm{T}}\mathbf{z} + 2(\mathbf{f}^{\mathrm{T}}\mathbf{z} + \mathrm{b}_2\mathbf{u}) \tag{10}$$

The first element of equation (10) is always negative, as the expression $\mathbf{e}^{\mathrm{T}}\mathbf{z} = \mathbf{e}^{\mathrm{T}}\mathbf{P}\mathbf{e}$, where $\mathbf{z} = \mathbf{P}\mathbf{e}$ is always positive. System (5) will then be asymptotically stable, i.e. its derivation will be negative, if for input u the following will apply

$$\mathbf{u} = -\mathrm{K}\mathbf{e}^{\mathrm{T}}\mathbf{z} \tag{11}$$

Note: The second element of equation (10) will be negative, if $\mathrm{b}_2\mathbf{u}$=-$\mathrm{b}_2\mathrm{K}\mathbf{e}^{\mathrm{T}}\mathbf{z}$ will be larger than $\mathbf{f}^{\mathbf{T}}\mathbf{z}$**,** which can always be assured by a sufficiently large value of optional positive parameter K**.**

For generating state quantities deviations of the reference model and the system according to equation (4) the following modification can be applied

$$e_3 = x_{\mathrm{eM}} - x_{\mathrm{e}} = \int x_{1\mathrm{M}}\,\mathrm{d}t - \int x_1\,\mathrm{d}t =$$

$$= \int (x_{1\mathrm{M}} - x_1)\mathrm{d}t = \int e_1 \mathrm{d}t \qquad (12)$$

The resulting block diagram of CL middle section tension control is shown in Fig. 4.

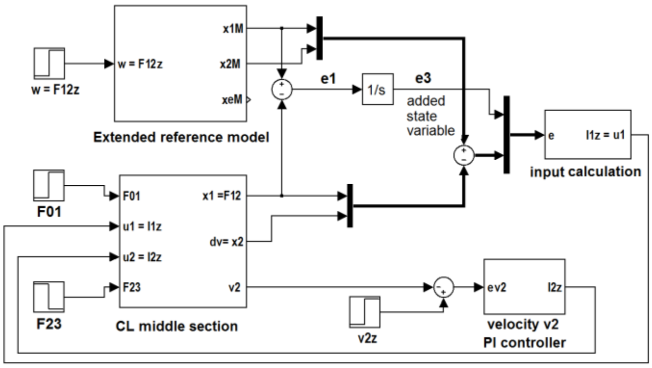

Fig. 4 Block diagram of CL tension control

2.3 Experimental verification on HIL platform

The properties of the proposed controller were verified by experimental measurement on a new concept of hardware-in-the-loop (HIL) simulation platform (Fig.5).

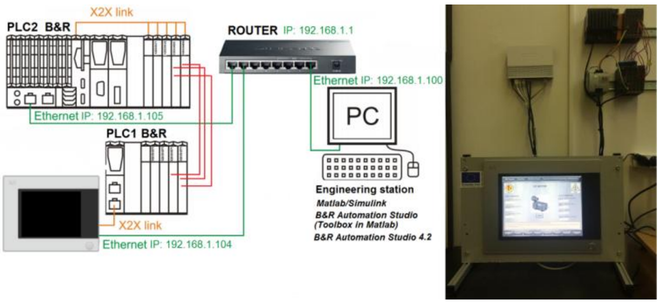

Fig. 5 *HIL simulation workplace*

The workplace consists of two standard PLCs and one standard PC. Communication between these devices is via standardized Ethernet interface. The first PLC, equipped with an operator display, is used for modelling the controlled technological process. The operator display enables independent animation of the process model and also external modelling of various process situations (change of drive load torque). The second PLC is used as the control member of the system and enables testing of various controller options. Interface of control and information signals between the controller and the process model is implemented by standardized electric signals.

A standard PC with Windows operating system enables programming of both the control PLC and the PLC for technological process simulation. For this purpose it has to be provided with a programme package from the manufacturer of the PLCs being used, and possibly also software for dynamic systems modelling. As in this particular case PLCs from B@R were used, for their programming the programme package *B@R Automation Studio 4.2.* was installed on the PC. The *Matlab* package with the relevant tools was installed for modelling purposes.

The whole process of implementation of the specified task in the HIL simulation workplace is executed in four basic steps.

In the *first step*, the CL control (Fig. 4) was computer modelled in *Matlab* environment using *Simulink*.

In the *second step* it is necessary to build a hardware configuration for the process simulation PLC1 (PP500) and for the control PLC2 (X20 CP 1484-1.

In the *third step* it is necessary to transform from Matlab the CL model (Fig. 2) and its reference model into the source code for PLC1 for process simulation and the controller structures (Fig. 4) into the source code for the control PLC2. It was implemented by using the *B&R Automation Studio toolbox* in *Matlab* for automatic generation of the code for PLCs according to the *Simulink* block diagram created in the first step.

In the *fourth step* we verify the correctness of the tension controller design.

3 Results and discussion

The dynamical performance of the output controlled variable of tension F_{12} for the operation cycle which includes three stages – start-up, line running at constant operational speed, line run finish. for the value of parameter K=2 is illustrated in Fig. 6. It is evident that tension in the middle section of the continuous line practically follows the tension prescribed by the reference model during the whole operation cycle, and it does so even when influenced by step disturbances at its input and output at time t=3s and t=6s and also under the influence of all changes of speed (Fig. 7), which fact verifies the invariance of the proposed control against additive disturbances.

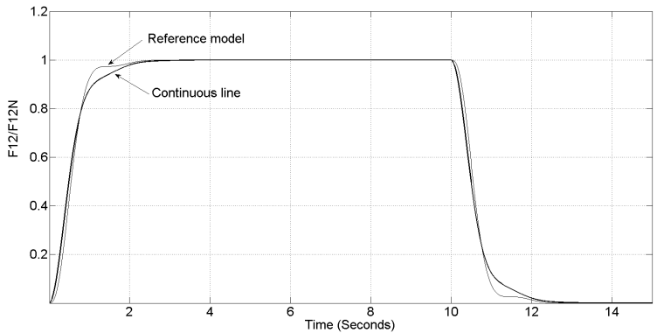

Fig. 6 Time course of tension control of CL

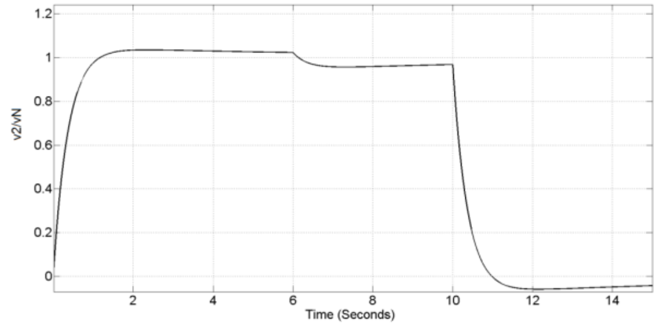

Fig. 7 *Time course of velocity v_2 control of CL*

The robustness of the proposed control structure was verified for changes in the two most important controlled system parameters that significantly influence the properties of flexible coupling, namely damping of the material being processed (material elasticity), and the moment of inertia of the drives (pulling thicker sheet metal, material weld). Figures 8 and 9 show the time plots of tension F_{12} for as much as fivefold reduced material damping (i.e. five times more elastic material) and for a twofold increase of the drives´ moment of inertia (parameter K=2).

It is clear from the quoted figures that the dynamics, autonomy and invariance of tension control practically did not change with the significant change of the parameters considered, which fact points at the strong robustness of the proposed controller.

Proposed control structure is very simple, and there is no need for a mathematical model of the system for the calculation of the controller parameters. The dynamical properties of tension setting are in general prescribed by a linear reference model in state space (Eq. 2), and stability is secured by the elements of positive definite matrix **P** (eq.9) and by choosing a positive parameter K.

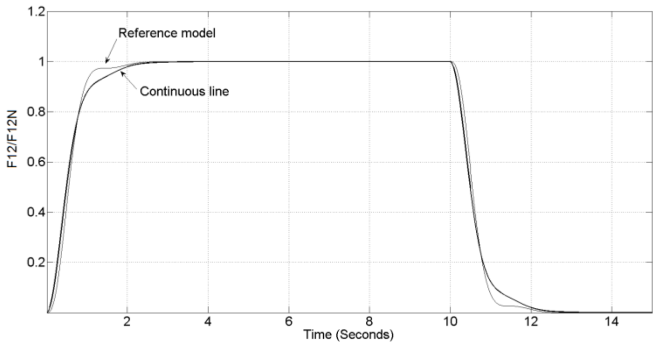

Fig. 8 *Time plot of CL tension control for K_t=0.2*K_{tN} and J=2*J_N*

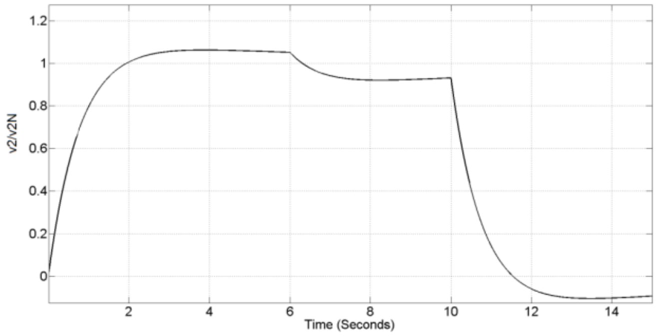

Fig. 9 *Time plot of CL velocity v_2 control for K_t=0.2*K_{tN} and J=2*J_N*

Controller synthesis requires data about all state quantities of the controlled system, which is the main disadvantage of the proposed stable control structure. However, the state quantities can be obtained either by measurement or from various types of observers.

4 Conclusion

The paper deals with the design and verification of a new stable control structure with reference model for the control of tension in the middle section of a continuous processing line.

Because the speed and tension subsystems of the line were considered as independent systems and the coupling between them was regarded as a disturbance the control of the continuous line output quantities (tension and speed) is decentralized. The controllers for each subsystems were then designed independently.

The properties of the proposed control structure were verified by experimental measurement on HIL platform based on PLC´s. The main advantage of the proposed control structure is its strong robustness over a wide range of changes of significant parameters of the controlled system, together with other important objectives of CL control, i.e. invariance and desired dynamics prescribed by the reference model both in transient and in steady states. What is more, the Lyapunov synthesis tools guarantee the stability of the whole controlled system.

The proposed control strategy is very simple and therefore it is possible to assume its wide application in industrial practice.

Appendix

Parameters of CL used for simulation:

DC motors:

U_N =24 V	n_N =3650 rpm-s	R_A=0.7 Ω	I_N=8.5 A
P_N = 140 W	J=0.002 kgm^2	M_N=0.37 Nm	L_A =0.1 mH
j=24	cϕ=0.043 Vs	v_{MAX} =0.6 ms^{-1}	I_{MAX} =20 A
F_{12N} =25 N	K_{RI}=1 V/A (current sensor)		

Processed material:

b=0.03 m, h=0.1·10^{-3} m, S=bh=3 10^{-6}, E=1.8·10^9 Nm^{-2}, SE=5400 N, T_{12}=2.25 s, l_{12}=1.35 m, $K_{tN} = \frac{Jj^2}{T_{12} 2r^2} = 160\ kgs^{-1}$

Work rolls: r=0.04 m Reference model: α=5

Parameters of PI controller of velocity v_2: K_P=20, K_I=2

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