MODEL-BASED CONTROL OF LATERAL WEB BEHAVIOR - AN INTERCONNECTION OF TWO WEB GUIDING SYSTEMS WITHIN PACKAGING MACHINERY

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ABSTRACT

Within packaging industry mostly web materials are used to form bags or similar shaped packages. In order to professionally convert these materials and achieving increasing quality requirements of bags, detailed knowledge of lateral web dynamics is mandatory. One major problem of vertical form fill and seal machines is accuracy of the lateral web positioning process of multi-layer webs. To obtain a high quality bag with minor visibility of inner web layer, positioning accuracy has to be $\pm\ 0.5\ mm$. Due to different converting steps within a vertical form fill and seal machine and necessity of positioning for each step, more than one web guiding system is required. This leads to the major problem, which is solved within this paper: the combination of two web guiding systems within a vertical form fill and seal machine.

First of all, this paper shows some of the most important milestones within research work of lateral web dynamics presenting the current state of the art. A special approach of hybrid modeling the lateral web behavior is established as well. Thus, a hybrid model of a rotating frame system can be introduced. Direct use of the model within a machine control leads to the hybrid modeling approach. Measurements and simulation results are matching with less than $\pm\ 0.5\ mm$ difference.

After introducing the hybrid modeling approach of a rotating frame system, interconnection strategies of a lateral moveable web roll system and the mentioned rotating frame system are given. To reach the target of combining these systems with the mentioned positioning accuracy and usability of a certain controller directly on a machine control unit, different types of controllers are developed and evaluated. A PID-controller analyzed firstly in this paper shows good results but doesn't achieve the target accuracy. The next investigated controller is a model-based control algorithm. This uses the simulated lateral web behavior, induced by the lateral movable web role, to predict and calculate the needed movement of rotating frame system in order to e.g. compensate the movement. With this method, results in the needed accuracy range are achieved and assured by measurements. However, the issue of exceeding the accuracy level due to differences between simulated and real web behavior still exists.

A controller containing a tuned PID-controller and a model-based control algorithm is investigated at the end of this paper via a simulation and achieves the accuracy range of ± 0.5 mm despite of high position differences between simulated and real web behavior. Summarized, the paper presents simulation and control methods of lateral web behavior, which can be directly computed and used on a machine control unit with very good results.

NOMENCLATURE

RF	rotating frame
SR	sliding roller
BPM	bags per minute
PID	proportional-integral-derivative
SRC	sliding roller controller
MPC	model predictive controller
OEE	overall equipment effectiveness
R2R	roll-to-roll

INTRODUCTION

Scientific investigations of packaging processes are quite young in contrast to other academic fields. First well known scientific studies exist since 1920. In that time period E. Sachsenberg worked on functionality, design, standardization and economics of packages [1]. These studies were made at technical university of Dresden and generated the base for further research work concerning new packaging methods and styles. Due to this developments the packaging industry grows with a lot of new developed equipment. Today most of the packaging processes can be handled with more or less effort. However, packaging technology is pressurized by different influences. Most responsible for high pressure within packaging technology are the costs per package which are leading to the necessity of optimized processes. From customer side the machine builder gets high requirements regarding overall equipment effectiveness (OEE), which are additionally to costs per package.

One example of highly influenced machines is a vertical form fill and seal machine (VFFS), because it is working mostly at the end of the value-added chain within primary packaging sector. Such a machine is shown in figure 1 on the left side. Basically it consists of a forming shoulder which forms the web to a tube around the forming tube and draw-off belts to transport the film. Additionally the machine has two web guiding systems: the rotating frame (RF) and the movable film role called sliding roller (SR). On the right side of the figure some bag-styles are displayed. The full corner bag is the most complex bag regarding automation of a VFFS because the film has to be positioned at two different converting steps with two web guiding systems. These web guiding systems are influenced by each other.

To reach a high OEE and low costs per package, positioning of film has to be in an accuracy range of ± 0.5 mm. Especially this high level of positioning quality is necessary in case of producing full corner bags. These bags are mostly packages for high quality long seam. The high positioning quality is required, because the inner layer of used multilayer films should not be seen at the corner. The current state of the art regarding positioning accuracy is ± 1 mm. Another perspective is to produce VFFS as cheap as possible. That means use of easiest control units, less sensors as possible and implementation of simulations with low calculation effort.

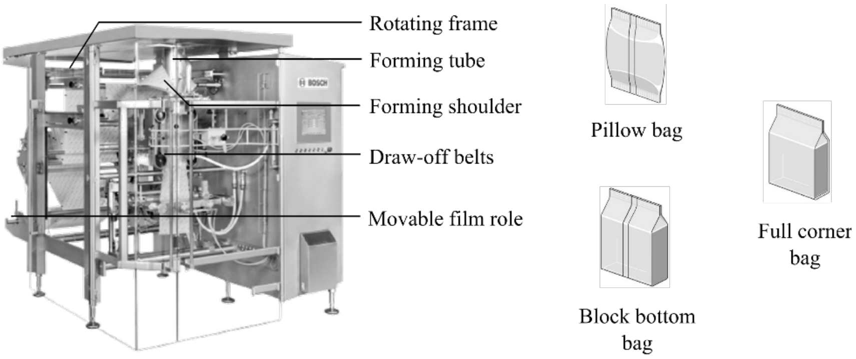

Figure 1 – left: VFFS with main parts, right: examples of bag styles

Dealing with this requirements leads to hybrid modeling approaches. A hybrid modeling approach is mostly used in industry environment [2] to achieve very fast good simulation results. Besides *"grey box"* - models, how hybrid models are often called, *"black box"* - models and *"white box"* - models are existing. *"White box"* - models using a huge physical knowledge to determine the behavior of system and mostly are based on mathematic equations.

"Black box" - models are based on a huge amount of empirical knowledge e.g. measured system answers and do not use physical based equations to describe the behavior of an investigated system. The complexity of both leads often to the combination of both approaches – *"grey box"*-models. An Overview of these different modeling paradigms including the initial position of modeling is given by [2] and shown in figure 2.

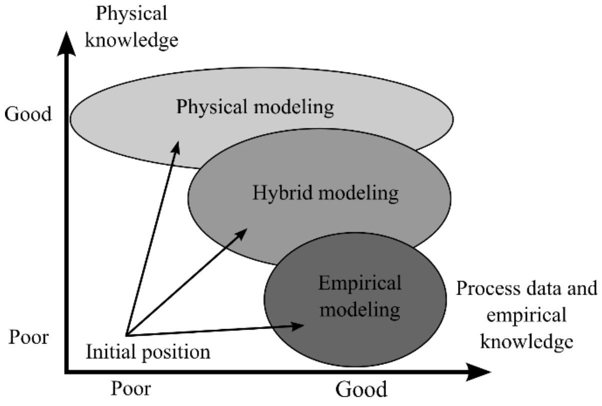

Figure 2 – Paradigms of different modeling methods [2]

LATERAL WEB DYNAMICS

The topic of the present paper is based on lateral dynamics of web materials and new simulation approaches. Thus, within this section a small overview of existing research work is given. The overview includes the most important milestones of research work and extends the physical modeling of lateral web behavior through a hybrid modeling approach.

Milestones Within Research Of Lateral Web Dynamics

The investigation of lateral web behavior started more than 50 years ago, starting by treating the web as a string. A roll-to-roll (R2R) system is a typical system used within converting machines like printing, packaging or paper producing machines. Modeling of such complex machines can take advantage of these modular, combinable systems. To describe the behavior of a web within R2R systems, [3] assumed the web as a tensioned Euler-Bernoulli beam. Based on that perception, lateral web behavior is modeled as a fourth-order partial differential equation, shown in equation {1}. Parameter K^2 in equation {2} comprises the web tension T within the R2R section and the bending stiffness of the web EI. Parameters x and y are coordinates within transport direction and orthogonal to that.

$$\frac{\partial^4 y}{\partial x^4} - K^2 \frac{\partial^2 y}{\partial x^2} = 0 \qquad \{1\}$$

$$K^2 = \frac{T}{EI} \qquad \{2\}$$

Based on the comprehensive study in [3] further fundamental investigations have been published. On the one hand the lateral behavior of a real web [4] and on the other hand the lateral behavior of an idealized web [5]. These three publications still are used in most instances to develop and evaluate different types of control algorithms until today. The assumption of web material as a tensioned Euler-Bernoulli beam is extended by [6] with the shear stiffness of the web AG. The parameter K^2 (eq.{2}) extends as shown in equation {3} and represents, inserted in equation {1} the assumption of the web as Timoshenko-beam, used in [6]. Further investigations [7–10] and modeling approaches [11, 12] with lower impact than [3] and [6] are here exemplary mentioned. Especially [12] is showing an interesting approach by assuming the web as plurality of threads.

$$K^2 = \frac{T}{EI\left(1+\frac{nT}{AG}\right)} \qquad \{3\}$$

Creating a *"white box"*-model consists of finding physical equations on the one hand and solving them on the other. A general solution of equation {1} is given by [13] and shown in equation {4}. $C_1 \ldots C_4$ are constants, which have to be defined using boundary conditions of R2R - systems. The boundary conditions of a R2R-system are presented in figure 3.

$$y = C_1 sinhKx + C_2 coshKx + C_3 x + C_4 \qquad \{4\}$$

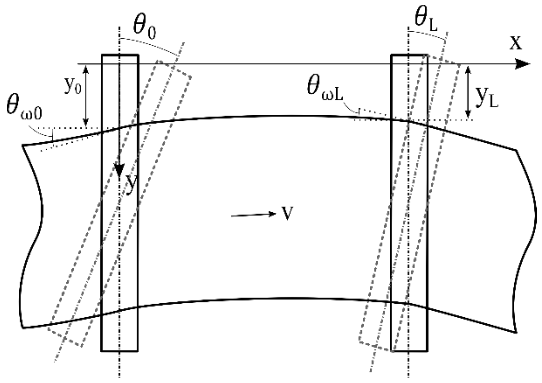

Figure 3 – Boundary conditions of lateral web dynamics including angular displacement of rollers [13]

Based on figure 3, mathematical descriptions of the boundary conditions can be obtained as shown in the following equation {5} and leading to subsequent constants $C_1 \ldots C_4$ presented in [13].

$$\begin{aligned} y|_{x=0} &= y_0 \\ y|_{x=L} &= y_L \\ \left.\frac{\partial y}{\partial x}\right|_{x=0} &= \theta_{\omega 0} \\ \left.\frac{\partial y}{\partial x}\right|_{x=L} &= \theta_{\omega L} \end{aligned} \qquad \{5\}$$

Still necessary to solve the fourth-order partial differential equation {1} are the lateral velocity (eq.{6}) of the web between to fixed rollers and the corresponding lateral acceleration (eq.{7}), where v is the web speed, respectively. With this parameters the not measurable parameters $\theta_{\omega 0}$ and $\theta_{\omega L}$ can be described, by assuming the web entering on the roller orthogonal to his rotation axle. Noticeable is the fact that the second order derivative is not directly the derivative of the lateral speed. An explanation of that is mentioned within [3].

$$\frac{dy_i}{dt} = v^2 \left(\theta_i - \left.\frac{\partial y}{\partial x}\right|_{x=i}\right) + \frac{dz_i}{dt} \qquad \{6\}$$

$$\frac{dy_i}{dt} = v^2 \left(\theta_i - \left.\frac{\partial y}{\partial x}\right|_{x=i}\right) + \frac{dz_i}{dt} \qquad \{7\}$$

Using the constants $C_1 \ldots C_4$ presented in [13] leads to the second-order partial derivative (eq. {8}) at position L. L means here the span length, respectively.

$$\left.\frac{d^2 y}{dx^2}\right|_{x=L} = \frac{1}{L^2} f_1(KL)(y_0 - y_L) + \frac{1}{L} f_2(KL)\theta_{\omega L} + \frac{1}{L} f_3(KL)\theta_{\omega 0} \qquad \{8\}$$

with

$$f_1(KL) = \frac{(KL)^2 \cosh(KL) - 1}{KLsinh(KL) + 2[1 - \cosh(KL)]} \qquad \{9\}$$

$$f_2(KL) = \frac{KL[KLcosh(KL) - \sinh(KL)]}{KLsinh(KL) + 2[1 - \cosh(KL)]} \qquad \{10\}$$

$$f_3(KL) = \frac{KL[cosh(KL) - \mathrm{KL}]}{KLsinh(KL) + 2[1 - \cosh(KL)]} \qquad \{11\}$$

The combination of equation {6}, {7} and {8} leads to a solution of equation {1} within time domain. Use of a Laplace-transformation leads to a general *"white box"*-model with a huge amount of influencing parameters, presented in [13]. This model can be reduced by special boundary conditions. In case of two fixed, parallel rollers means that $z_0(s) = z_L(s) = \theta_0(s) = \theta_L(s) = 0$. A system with a PDT2-character is obtained (eq. {12}).

$$\frac{Y_L(s)}{Y_0(s)} = \frac{-\frac{1}{\tau} f_3(KL)s + \frac{1}{\tau^2} f_1(KL)}{s^2 + \frac{1}{\tau} f_2(KL)s + \frac{1}{\tau^2} f_1(KL)} \qquad \{12\}$$

with

$$\tau = \frac{L}{v} \qquad \{13\}$$

The in equation {12} obtained model acquires a lot of calculation power if it's combined e.g. 13 times for a machine application, especially when the machine has to adapt the combined model to changing web parameters or changing lengths within dancer systems. The adaptation is needed in case of frequently changed web materials as is daily business within packaging industry.

Physical Models Of Rotating Frame Systems

Web guiding systems can be divided into two common guides, the remotely pivoted guide and the offset-pivot guide. The present paper is focus on the secondly named offset-pivot guide, which is below named as RF-system. The RF-system has been investigated in several studies to optimize control algorithms and to reach high web positioning accuracy.

A physical model of a RF-system based on the fourth-order partial equation {1} of [3] published by [13] is given in the following equation.

$$G(s) = \frac{s^2 + \frac{1}{\tau} f_2(KL)s + \frac{1}{\tau^2} f_2(KL)}{s^2 + \frac{1}{\tau} f_2(KL)s + \frac{1}{\tau^2} f_1(KL)} \qquad \{14\}$$

A simplification of this model is carried out within [14] and given in equation {15}. However, the simplification remains a second order model and takes into account physical properties of the web. The lower quality first order model assumes a straight span and does not reach the necessary accuracy.

$$G(s) = \frac{\frac{1}{\tau^2} f_2(KL)}{s^2 + \frac{1}{\tau} f_2(KL)s + \frac{1}{\tau^2} f_1(KL)} = \frac{\frac{f_2(KL)}{f_1(KL)}}{\frac{\tau^2}{f_1(KL)} s^2 + \tau \frac{f_2(KL)}{f_1(KL)} s + 1} \qquad \{15\}$$

Hybrid Modeling Of Lateral Web Behavior

The previous mentioned models belong to the class of *"white box"*-models and reproduce the real system behavior very good. To understand and adapt this physical based models comprehensive understanding of these models is necessary. Thus, adaptation within industry fields is critical. Especially, if the combination of a plurality of R2R systems without knowledge of used web material is required the calculation effort regarding adaptation of the model to the real world increases. Doing this calculations on cost effective machine control e.g. within packaging machinery is impossible. Thus, a hybrid modeling approach has been investigated in [15].

Major target of this study was the simulation of lateral web behavior within a VFFS, directly calculated on the internal machine control. Due to the complex boundary conditions: partly intermittent web transport, non-steady movement of a dancer system, high accuracy level of simulation within ± 0.5 mm and the necessity to combine 13 R2R sections the physical model in equation {1} is not applicable.

The model, which has been investigated firstly was a first-order model analog to that published in [5]. Due to insufficient simulation quality the system has been extended to an adaptive second-order model (eq. {16}), where k is an adjustment parameter, respectively. The time constant τ is the same as in equation {13}.

$$\frac{Y_L(s)}{Y_0(s)} = \frac{1}{k\tau s^2 + \tau s + 1} \qquad \{16\}$$

In addition, first optimizations regarding influence of the dancer system has been made because the quality of the simulation was not within ± 0.5 mm. Due to the high influence of the dancer system and resulting non-steady web transport the time constant has been discretized by using the mean value $\bar{L}$ (eq. {17}) of span length and the discretized value of web speed $\bar{v}$ (eq. {18}) within one period of dancer movement. $\bar{v}$ is assumed as a sum of basic machine speed v_0 and mean speed of the span within dancer system combined with an adjustment parameter p. Advantage of the discretized time constant τ^* (eq. {19}) is the use of calculated time constant within the next period of dancer arm movement to simulate the web behavior of the 13-section model.

$$\bar{L} = \frac{L_{i_{max}} + L_{i+1_{max}}}{2} \qquad \{17\}$$

$$\bar{v} = v_o + \frac{L_{i_{max}} - L_{i_{min}}}{2\left(t_{i_{min}} - t_{i_{max}}\right)p} \qquad \{18\}$$

$$t^* = \frac{\bar{L}}{\bar{v}} \qquad \{19\}$$

By use of equation {19} the one-parameter model (eq. {16}) becomes a two-parameter model shown in equation {20} and reaches the required accuracy level. In addition, the adjustment parameter k and p are the same for each of the 13 R2R systems. This leads to a better calculability on a machine control because the parameters are 26 times used within the whole model. In contrast the parameter K in an equivalent model based on equation {12} is used 299 times.

$$\frac{Y_L(s)}{Y_0(s)} = \frac{1}{k\tau^* s^2 + \tau^* s + 1} \qquad \{20\}$$

INTERCONNECTION STRATEGIES AND SYSTEM DESCRIPTION

The VFFS shown in figure 1 is the base for investigations of interconnection strategies of two web guiding systems without use of additional sensors. That means both systems influencing the web position have to be combined via robust simulation methods, so that the VFFS remains operational despite arising system disturbances. Besides that the web position at the forming shoulder, while simultaneously working SR and RF system has to stay within an accuracy level of ± 0.5 *mm*. Especially, this high requirement arises from the high quality demand within the production of full corner bags (figure 1). Additionally the machine has to keep itself running, despite of web deviations. With the current state of the art of VFFS this requirement is not accomplishable. The machine has to be stopped while manual readjustments of web role and RF system have to be made.

In addition to the constraints of the production side the machine itself creates boundaries, which have to take into account. To better describe these boundary conditions, within figure 4, the in figure 1 introduced VFFS is shown schematically. Conspicuously, the machine works with two different dancer systems, which divides the machine into two different sections. One section with quasi-stationary web transport, because the movement of dancer 2 has an amplitude of 0.5° on the one hand and one section with nonsteady web transport, because of the movement of dancer 1 with an amplitude of 7.5° on the other hand. The transition either systems is within the system boundary of the simulation system. A solution for different web speeds and influences of simulating the lateral web behavior is carried out by [15].

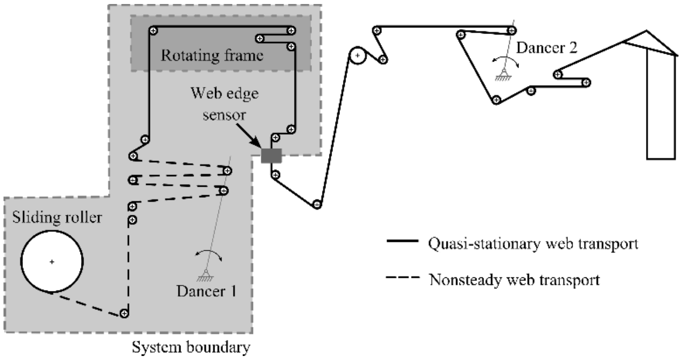

Figure 4 – Schematic system description of the investigated VFFS

Interconnection of both web guiding systems presented within this paper is based on the strategy of compensating the web position change, introduced by SR system, through RF system. This interconnection strategy is able to accomplish the above mentioned requirements with two restrictions: it has to be calculable on a machine controller and it has to be self-adjustable to different web materials.

One, on a machine control calculable, system with which the requirements can be reached, is already introduced by [15]. This simulation approach has to be investigated regarding the usability for RF systems. Besides this task controller developments have to be examined. To develop a robust system, the controller has to deal with disturbances of web behavior, with deviations between simulation and real system behavior and at least it has to be adaptable to changing web characteristics.

HYBRID MODELING OF ROTATING FRAME SYSTEM

Based on the above mentioned hybrid modeling approach which starts modeling the system as an idealized model, the here introduced model of a RF system will be investigated. Target of this approach is to reach a simulation accuracy of ± 0.5 *mm*. In addition to the high level of simulation accuracy, the system should be adjustable very easy to the real plant without knowledge of the used web material.

Modeling of Rotating Frame with an Idealized System

A RF system shown in figure 5 contains a rotating carrier with two rotating rollers A and B and two fixed rollers. One of them, roller C, is exemplary shown after the rotating carrier. The other one is positioned in front of the rotating carrier with the same span length as between the rollers B and C. The rotating carrier turning a certain angle $\varphi(t)$ around the pivot point O leads to a lateral web displacement $y(t)$ on the fixed roller C. The dynamic of the system is influenced by the web speed v and the length of the sections L_1 and $L_2(t)$.

The following modeling approach is based on the following assumptions: the web is a straight span without bending and elastic deformations and the friction between web and rollers A and B prohibits lateral slippage. Additionally the angles $\varphi(t)$ and $\theta(t)$ are hold so small that equation {21} and equation {22} applying.

$$sin\varphi(t) \approx \varphi(t) \qquad \{21\}$$

$$tan\theta(t) \approx \theta(t) \qquad \{22\}$$

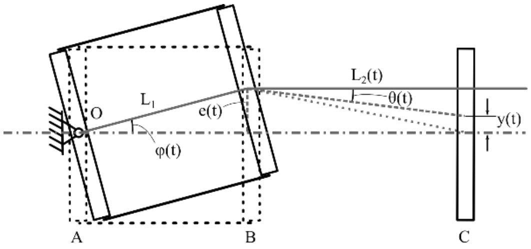

Figure 5 – Schematic overview of a RF system

The lateral web displacement can be described accordingly figure 5 as

$$y(t) = v(t) \int sin\theta(t)dt \qquad \{23\}$$

and the web offset angle θ is calculated as

$$tan\theta(t) = \frac{e(t)-y(t)}{L_2(t)} \qquad \{24\}$$

with

$$e(t) = L_1 sin\varphi(t) \qquad \{25\}$$

Combining the Laplace-transformation of equation {21} and the Laplace-transformation of the combination of the equations {21} and {22} leads to a first-order model {26} with PT1-characteristic. The time constant τ_2 is here $\tau_2 = L_2/v$.

$$G(s) = \frac{Y(s)}{\Phi(t)} = \frac{L_1 v}{L_2 s + v} = \frac{L_1}{\tau_2 s + 1} \qquad \{26\}$$

The adaptation of the above mentioned model is investigated within [16] and showed, that the angle φ is not directly measurable. The motorized RF system is rotated by a motor which changes the length $b(t)$ as shown in figure 6. Depending on maximum angle $\varphi_{max} \approx 1.25°$, calculated with a span length $L_1 = 460\ mm$ and a maximum lateral web displacement of 10mm, the assumption in equation {27} is applicable.

$$\varphi(t) \approx \alpha(t) - \qquad \{27\}$$

The included angle $\alpha(t)$ can be obtained by the law of cosines:

$$\alpha(t) = \arccos \frac{a^2 + b(t)^2 - c^2}{2ab(t)} \qquad \{28\}$$

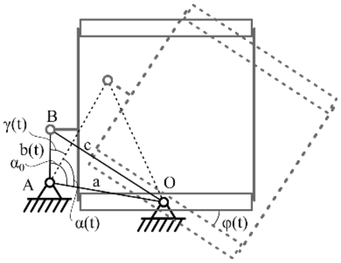

Figure 6 – Sketch of real RF system within VFFS

To reduce the calculation effort within the machine control of a VFFS machine and due to the small angle φ_{max} equation {28} has to be linearized around α_0 with the motor length b_0. Afterwards, equation {27} can be written as

$$\varphi(t) = \Delta\alpha(t) = \varepsilon(b(t) - b_0) = \varepsilon \Delta b(t) \qquad \{29\}$$

with the parameter ε calculated with $a = 388\ mm$, $b_0 = 195\ mm$ and $c = 462.5\ mm$.

$$\varepsilon = \left.\frac{d\alpha}{db}\right|_{b=b_0} = -\frac{1}{\sqrt{1-\left(\frac{a^2+b_0^2-c^2}{2ab_0}\right)^2}} \frac{4ab_0^2 - 2a(a^2+b_0^2-c^2}{(2ab_0)^2} = -3.485 * 10^{-3} \qquad \{30\}$$

With the equation {29} including $\Delta b(t)$ calculated as product of the pitch of linear axle per step of the motor δ and the amount of motor steps N equation {26} can be obtained as shown in equation {31}.

$$G(s) = \frac{Y(s)}{N(s)} = \frac{K}{\tau_2 s + 1} = \frac{L_1 \varepsilon \delta}{\tau_2 s + 1} \qquad \{31\}$$

The gain K can be calculated with $\delta = 2 * 10^{-3}\ mm$ as $K = 3.22 * 10^{-3} \frac{mm}{step}$. The amount of needed steps N of the stepper motor to adjust 1 mm web displacement is obtained as shown in equation {32}. Afterwards, this value is used to scale the measured position of the stepper motor within the diagrams.

$$\frac{1}{K} \approx 310 \frac{steps}{mm} \qquad \{32\}$$

The evaluation of the first-order model with idealized web behavior is shown in figure 7. Observably, the real system response and the simulated system response do not match each other. The deviation between simulated web position and real web position exceeds the required accuracy level. The same result has been reached within [15] with simulating the lateral web behavior of a SR introduced position change.

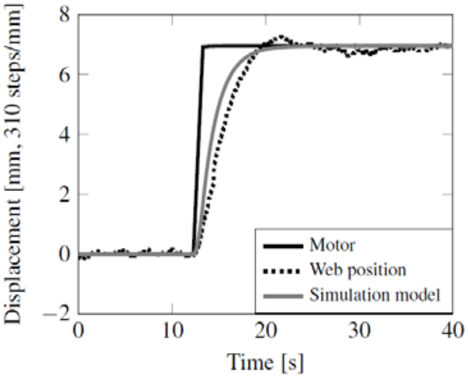

Figure 7 – Evaluation of first-order RF model with idealized web behavior (machine speed = 60 BPM, bag length = 200 mm and displacement = 7 mm)

Hybrid Modeling Of Rotating Frame

Insufficient results of the first-order model using idealized web behavior (eq. {31}) is leading to hybrid modeling approach, introduced within this section. Firstly an investigation regarding a first-order approach based on equation {31} is carried out. An adjustment parameter p is introduced to adapt the time constant τ_2 within equation {33}.

$$G(s) = \frac{Y(s)}{N(s)} = \frac{K}{p\tau_2 s+1} \qquad \{33\}$$

By testing collected step response data of the VFFS at every packaging speed an optimal adjustment parameter p_{opt} of the semi-empirical model has been identified [16]. The first-order hybrid model (eq. {33}) with the parameter $p_{opt} = 1.38$ fits the system behavior better then the idealized first-order model (eq. {31}) but still not good enough to reach the required accuracy level [16]. Even though the first-order model fits the real system behavior quite well, physical models (eq. {14} and eq. {15}) describing a second-order model. Taking this and the complexity of $f_1(KL)$ (eq. {9}) and $f_2(KL)$ (eq. {10}) into account leads to a second-order hybrid model introduced with equation {34}. The second time constant is the square of the first time constant adjustable by parameter k. Parameter k includes the square of the first adjustment parameter p to reduce the complexity.

$$G(s) = \frac{Y(s)}{N(s)} = \frac{K}{k\tau_2^2 s^2+p\tau_2 s+1} \qquad \{34\}$$

Analogue to the first-order hybrid modeling approach, optimal adjustment parameter can be obtained as: $k_{RFopt} = 0.5$ and $p_{RFopt} = 1.46$. Figure 8 shows evaluations of the second-order hybrid modeling approach of a RF system depending on different machine speeds and position steps. It can be seen, that the quality of the model with optimal adjustment parameters simulates the real system behavior very well. This high simulation accuracy is independent of the checked parameters. The disturbance within the left diagram of figure 8 remains within the required accuracy level. Thus, it is acceptable to work with an optimal adjustment parameter set within a second-order hybrid model.

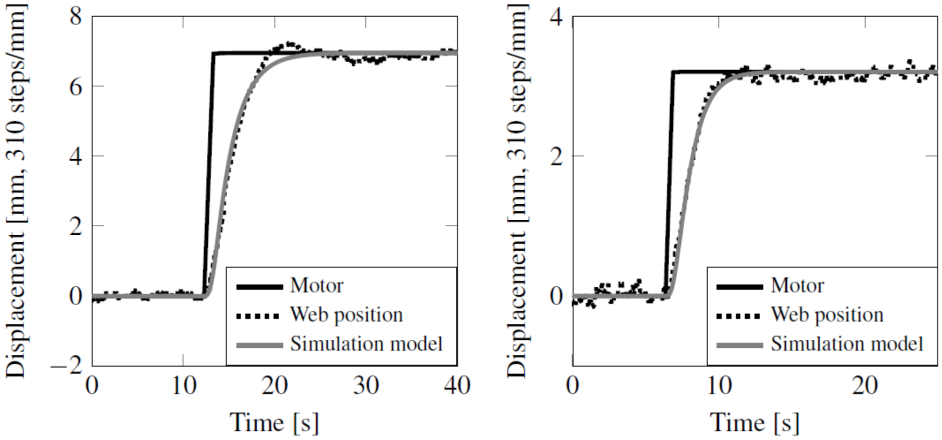

Figure 8 – Evaluation of second- order hybrid model (machine speed =60 BPM(l), 100 BPM (r), bag length = 200 mm (l,r), step = 7mm (l), 3.25 mm (r))

CONTROLLER DEVELOPMENT TO INTERCONNECT TWO WEB GUIDNG SYSTEMS

Evaluation of a PID-Controller

A well-known and within industry common used controller is a proportional-integral-derivative (PID) controller. Firstly, this type of controller will be investigated within this paper. Basically an unlimited PID-controller can’t be used to control the RF system modeled by equation {31} because of technical boundaries given by the VFFS. Thus, a standard PID-controller is combined with a rate limit unit and a saturation unit. These two additional units comprises the maximum speed (4000 *steps/s*) and the movement range (± 3100 *steps*) of the stepper motor of the RF system. The rate limit of ±13 and the saturation of ±10 can be obtained by using these technical boundaries.

Tuning the parameters K_P, K_I and K_D of the PID-controller reaches the objectives: no overshoot of the web response, no steady-state error, small settling time and a small number of motor steering’s. Parameter tuning (table 1) has been carried out with $K = 1/310$, $p = 1.46$, $k = 0.5$, $L_2 = 350\ mm$ and $v = 200\ mm/s$.

Packaging speed [bpm]	20	40	60	80	100	120	140
K_P	15	11	7	5	4	3	2
K_I	0.4	0.5	0.6	0.7	0.8	0.9	1.0
K_D	15	10	5	3	2	1	0.5

Table 1 – Tuning parameters of PID-controller depending on machine speed [16]

An evaluation of this limited PID-controller is done by implementation and test. The results are shown in figure 9. As can be seen the web is deflected at t_1 and the PID-controller directly starts to deflect the rotating frame system to bring the web position back to set position. The web position stays within the required accuracy level, controlled by the PID-controller obvious through the movement of the RF system. At time t_2 the SR system introduces a position change of the web, which leads to a reaction of the PID-controlled RF system. Obviously, the web position exceeds the specified accuracy level. Thus, the PID-controller can't be used to interconnect the above mentioned web guiding systems.

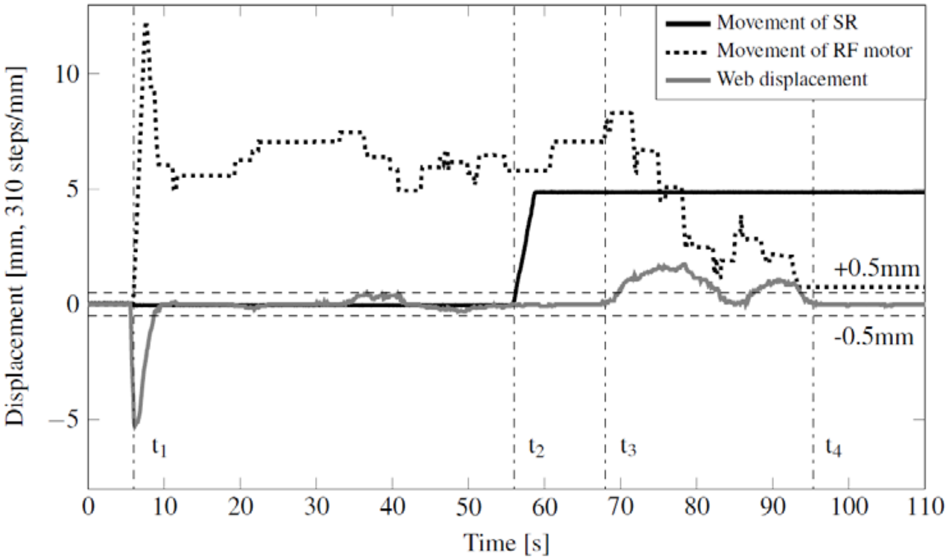

Figure 9 – Evaluation of PID-controller (machine speed = 60 BPM)

Development Of A Model Predictive Controller

One disadvantage of the above introduced PID-controller is the missing connection to the SR system. Lateral web displacement introduced by the SR system can't be predicted and controlled, because the big lateral displacement exceeds the capabilities of the PID-controller tuned to small displacements. Thus, a model predictive controller will be investigated within this section. The structure, shown in figure 10 represents an interconnection of a SR system with a RF system by using the 13-section R2R model of [15] and the model of a RF system (eq. {34}). Basically the controller uses the simulation result of the 13-section R2R model as an input of the inversed model of the RF system to calculate the RF system movement. This predicted movement of RF system compensates with the RF system behavior (eq. {34}) the web displacement introduced by SR system and accomplishes the interconnection target.

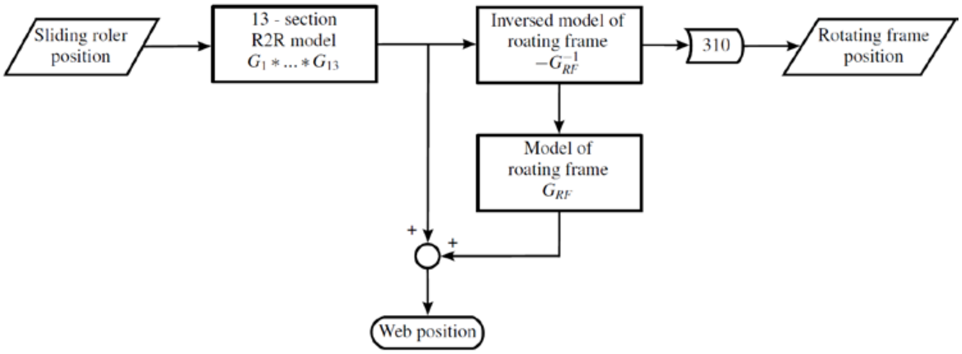

Figure 10 – Structure of a model predictive controller

The calculation of the inversed model represented in the following is exemplary discussed for the RF system model with above mentioned parameters (eq. {35}).

$$G_{RF}(s) = \frac{310}{1.531s^2+2.555s+1} \tag*{\{35\}}$$

As inversion of this transfer function with poles and without zeros is not possible, zeros have to be added to the system. Due to the two poles {36} and the influence of zeros within the range of the poles regarding the system dynamics, three zeros $z_1 = -30$, $z_2 = -31$ and $z_3 = -32$ are given to the system.

$$p_1 = -1.042 \qquad p_2 = -0.627 \tag*{\{36\}}$$

The system {35} changes to the system shown in the following equation {37}.

$$G'_{RF}(s) = \frac{310(s+30)(s+31)(s+32)}{1.531s^2+2.555s+1} = \frac{310(s^3+93s^2+2882s+29760)}{1.531s^2+2.555s+1} \tag*{\{37\}}$$

Equation (eq.{37}) can be inverted to obtain the inversed transfer function of the RF system (eq.{38}).

$$G'^{-1}_{RF}(s) = \frac{29760(1.531s^2+2.555s+1)}{310(s^3+93s^2+2882s+29760)} \tag*{\{38\}}$$

According to the structure of the model predictive controller within figure 10 a simulation is carried out with a measured web position difference introduced by the SR system. As can be seen in figure 11 the simulation result of the 13-section R2R system matches the real system behavior exceedingly good. The small deviations between the simulation and the web displacement by the SR system are random errors.

Based on the simulated web displacement, introduced by the SR system the web displacement to compensate the lateral position change can be obtained. It is the negative signal of the simulated web displacement by the SR system. Again this is used as an input into the inversed model of the RF system (eq. {38}) to predict the needed movement of the RF system.

The general web displacement shown within figure 11 represents the simulation result of the model predictive controller. As can be seen, the system works reliable and holds the web position within the accuracy level despite of the 10 *mm* big position difference.

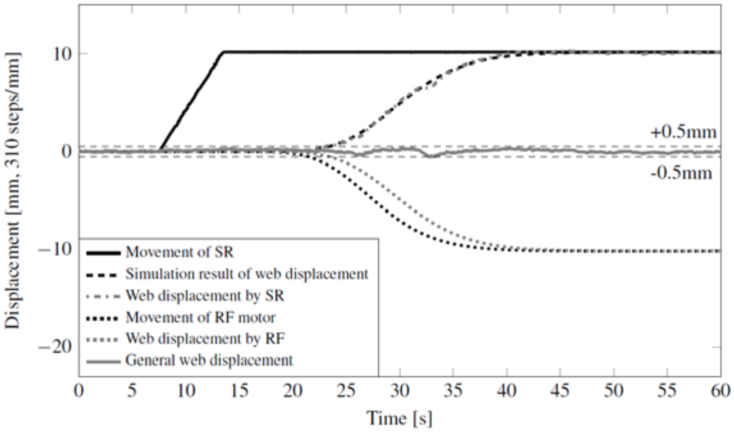

Figure 11 – Simulation of inverse model controller

To evaluate the simulation results the model predictive controller has been implemented within the VFFS. The measurement results are shown within the following diagram (figure 12). The measured web displacement staying within the accuracy level and the interconnection of both web guiding systems are accomplishing the main targets of the controller development.

The real web behavior follows the simulated curve for several seconds because of not simulated influences like friction or slip. However, the system shows a good performance. Despite of that the model predictive controller has one problem, which can lead to exceeding of the accuracy level. The model predictive controller can't handle deviations between simulated and real web behavior, not based on a lateral displacement of the web through the SR system.

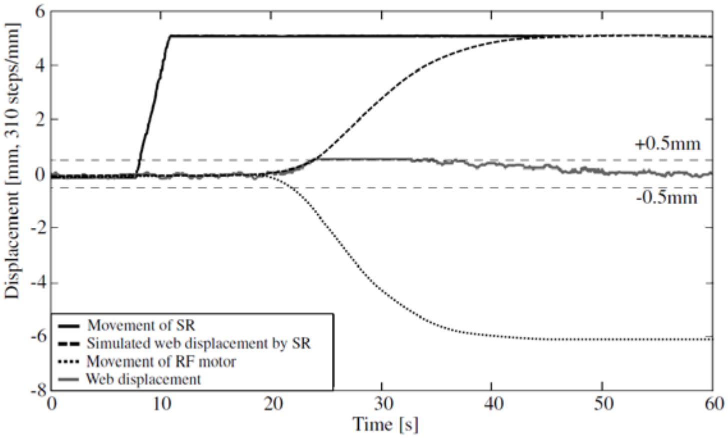

Figure 12 – Measurement results of an implemented model predictive controller (machine speed = 60 BPM, bag length = 200 mm, lateral web displacement = 5 mm)

Development of a Compound Model Predictive Controller

The model predictive controller introduced within the previous section interconnects two web guiding systems and requires low deviations between real and simulated system behavior of the 13-section R2R system. Related to the hybrid modeling approach of the lateral web behavior and the real machine behavior, it can be difficult to hold the web position within the required accuracy level.

Additionally to that the model predictive controller can’t compensate disturbances which are not introduced by the SR system. These disturbances can be compensated by a PID controller introduced within this paper as well. Putting all advantages together leads to a combination of a model predictive controller with a PID controller, shown in Figure 13.

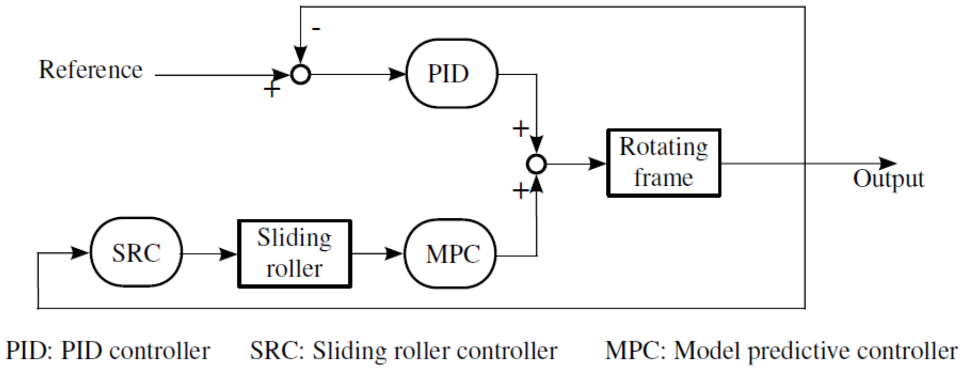

Figure 13 – Schematic overview of a compound model predictive controller

The compound model predictive controller combines the advantages of both previous mentioned controllers and prohibits that the disadvantages of each controller occur. This controller consists of a sliding roller controller (SRC), which controls the SR system, the 13-section R2R system, which is used as input of the model predictive controller (MPC) and a PID-controller. This combination leads to the advantage, that bad simulation results of the 13-section R2R system, shown in figure 14, can be compensated as well as random disturbances of lateral web position. Basically the strategy of a compound model predictive controller is a every time working PID-controller handling the secondly named issues, supported by a MPC predicting the lateral web displacement after web displacement by SR system.

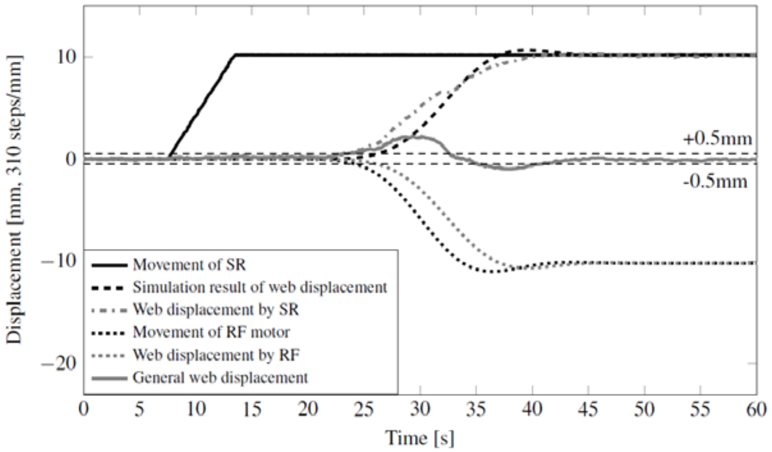

Figure 14 – Simulation of a model predictive controller with low-quality model of 13-section R2R system

The evaluation of the compound model predictive controller, shown in figure 15, is made with a simulation. As can be seen the matching quality of predicted and measured lateral web behavior is very low. Thus, the PID controller compensates these differences and keeps the simulated general web position within the required accuracy level. Otherwise the PID controller is supported by the model predictive controller getting just small web displacements to be compensated. Although this seems to need a lot of calculation effort, the system can be realized within the above mentioned VFFS machine control and does not require any additional control unit.

Summarized, the developments of all single controllers showing advantages and disadvantages. Thus, the combination of the PID controller and the MPC combining the advantages has been investigated and shows very good results, with low calculation effort. This makes the controller applicable within a VFFS, without any changes regarding controller hardware.

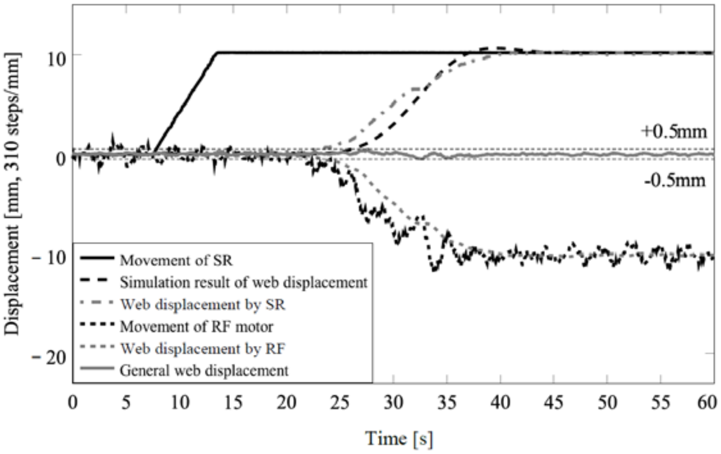

Figure 15 – Simulation of compound controller

CONCLUSIONS

Many modeling approaches of lateral web behavior suggests easy usability for controlling lateral web displacements within machinery. This paper carried out, that mostly physical based models are known and used to adjust controllers of rotating frame systems. Additionally it presents within the state of the art a hybrid modeling approach of lateral web behavior of multi section roll-to-roll systems. This approach is used to create a hybrid model of a rotating frame system, which succeeded. This modeling approach is used because of low calculation effort and thus usability within a machine control of a vertical form fill and seal (VFFS) machine.

The combination of the state of the art and the hybrid modeled rotating frame system to get an interconnected system with a web positioning accuracy of ± 0.5 *mm* is carried out. Additionally, this paper shows the recent state of the art of VFFS machines and introduces requirements and boundary conditions of two interconnected web guiding systems.

Based on the hybrid modeling of the rotating frame and the interconnection task, interconnection strategies were carried out and leading to the development of different controller algorithms.

Firstly, a common tuned PID controller is examined with bad interconnection capabilities, because the controller does not recognize, if a big or a small displacement arrives at the rotating frame and that’s why the displacement can’t be compensated.

Secondly the investigated model predictive controller shows very good results, both at simulation and implementation within a VFFS. Disadvantage of this controller is, that it is not able to compensate disturbances, which are not introduced by the sliding roller.

At least the combination of both controllers to a compound model predictive controller leads to an applicable solution, which took advantage of the advantages of each controller. This controller accomplishes the requirements and showed very good results within a simulation. The next step is the implementation of this controller within a VFFS to investigate the performance and robustness.

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