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Tension ripple-free dancer control of a web processing machine

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***Abstract*—Maintaining web tension in web processing line under changing web speed is a key factor in achieving good final product quality. Tension control systems with dancers play an integral role in such applications. A dancer roll system is essentially a preloaded idler arm with two machine tasks: imposing the web tension and acting as a controlling mechanism to avoid web damage caused by a range of mechanical issues like eccentric and non-circular web rolls or dynamic web speed trajectories. All the dancer control strategies described in literature have one thing in common: they do not adapt their control parameters to the type of web material. The characteristics of the web are not known in advance, and can vary from roll to roll and from time to time. Identification of the web parameters allows more advanced control. In this paper, a digital twin based feed forward controller is proposed to control the dancer in order to obtain variation-free even under varying web speed.**

***Index Terms*—web winding machine, web processing machine, tension control, dancer control, web handling**

I. Introduction

A web can be described as a flat material, such as textiles, papers, polymers, or metals whose thickness varies between a few micrometres to a centimetre and whose length can be up to several hundred metres and whose width is mainly determined by the web application and transportability limits [1]. Mainly to allow optimal transport of webs, the end product of a web processing machine is rolled up around a cardboard, metal or plastic tube [1]. Essentially, a web processing machine must often unwind and rewind the web at the right speed and tension to be able to perform the in-between operations under the right conditions. Main operations a web can undergo are printing, cutting, stamping, glueing, folding and packaging [2]. The process, or several processes in succession, can lead to changes in the web, e.g. stretching and stiffening of the web material which can cause the speed and tension of the web to be different when unwound and wound [3].

A web machine contains a mechatronic multi-motion system with actuators and sensors to control the speed and tension in a web to be handled. Maintaining web tension in the entire processing line under changing web speed is a key factor in achieving good final product quality [4]. Since the web speed can be easily controlled using feedback from speed sensors, the main issue is tight tension control, as discussed in detail in [1].

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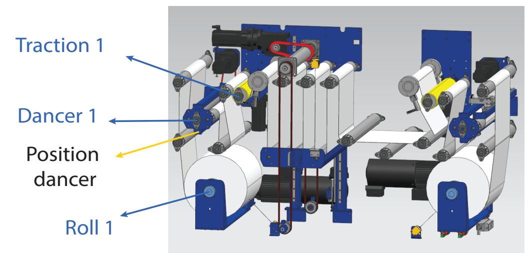

Fig. 1. The practical setup with indication of the actuators and sensors

Tension control systems with dancers or load cells play an integral role in maintaining constant tension during web transport. Dancer and load cell systems are used as a mechanism to correct a range of conditions. The unwinding roller may be slightly eccentric and non-circular, resulting in fast/slow feeding. There may be mechanical wear problems in the unwinding setup, such as worn bearings, alignment problems and similar mechanical inconsistencies. The processed material may also be prone to stretching and residual stress [3]. The process itself may have a start/stop function, as in a thermal sealing process [5]. These dynamic conditions, some of which occur simultaneously, cause stress transients in the web material.

The advantage of using load cells is the availability of direct tension information. The expensive cost and the need for periodic calibration often negated this advantage [6]. In [6], a disturbance observer together with Kalman filtered load cell feedback is proposed to achieve robustness against model variations and external disturbances. The direct measurement does also allow, for example, iterative learning sliding mode control for active wire tension control of automatic motor winding machines [7]. [3] proposes the design of multiple tension control zones, referred as roll-to-roll system, for flexible electronics that addresses film sagging under tension and deformation due to residual stress.

The main advantage of a dancer system is the web shortage or surplus compensating ability enables fast web resulting in faster roll acceleration and deceleration and faster load times than systems without storage capacity, such as load cell systems [6]. Two types of dancers, i.e. active and passive, are distinguished by their external actuator. In the active dancer, the position of the dancer roller is measured and the roller is forced by the external actuator to regulate tension disturbances. A desired force is mostly applied to the dancer by a pneumatic or hydraulic cylinder that is compensated by the web tension [4]. However, the passive dancer, consisting of a spring, damper and roller, has no external actuator [8]. Because rotary dancers are compact and convenient to manufacture, they are preferred to linear dancers [9].

Although dancers are a seemingly simple mechanism, there are complexities that can significantly affect system performance. One of the challenges in working with tension control systems is operating with closed-loop dancers. Customers increasingly want to use the full capacity of the machine resulting in the demand for higher web speeds. Besides passive, even active dancers may not be able to react quickly enough to maintain constant web tension and may cause the web to tremble. In order to cope with the aforementioned problems, in [8], the modelling of passive, active and hybrid dancer pendulum dancers is derived. The dynamics of the dancer types, with and without position feedback of the dancer roll, and the PI control of a driven roll are analyzed. [5] found that a reduced-order observer was required to estimate and control the tension disturbance over a wide frequency range.

All the previous dancer control strategies have one thing in common: they do not adapt their control to the type of web material. However, besides traditional unknowns in mechatronic systems, the machine has an additional inherent uncertainty. Namely, the characteristics of the web are not known, and can vary from roll to roll and from time to time (e.g. increasing stress after multiple runs) but are crucial for the proper operation of the machine. As the web is the linkage between all the actuators, knowing the physical parameters of the web will help to increase the web position and speed control performance, dancer control behaviour, roll quality, etc. All these settings are mainly tuned manually in industry until the customer's desired quality is obtained. This article focuses on optimizing dancer control based on web knowledge. Control of a gravity equilibrium two-roll dancer is analysed where in [3], [4], [8], [9], only the pendulum dancer has been considered. Observer loops as in [5], [6], [7] are avoided as these methods require extended offline tuning. Updating the closed-loop dancer control parameters based on web behaviour knowledge will lead to tension transient ripple-free control meaning higher web speed levels can be reached and more dynamic start-stop transients can be imposed for a larger stable and safe web tension region. Simulation results are presented to show the impact of knowing the web parameters on the dancer during start-stop and web speed level changes.

The main contributions of this paper are summarized as follows:

- A practical demo setup is presented and from this machine, the physical model is described. The dancer control equation is derived including the physical dancer and web parameters.
- A signal injection based method is presented to estimate the physical parameters of the web. A sine-wave tension excitation is imposed to the web. Analysing this tension trajectory and the resulting web extension using Sliding Discrete Fourier Transformation (SDFT) results in a web stiffness and damping estimation.
- After updating the digital model of the web winding machine with the obtained web estimates, machine control can be optimized by finding the new optimal dancer control parameters. This is validated on the unwinding group.

II. Practical setup with main web handle elements

A physical web processing unit is designed and build with the following dimensions: length 2.1 m, width 1.4 m, height 2.2 m, maximum web speed 120 m/min and maximum web tension 200 N. The maximum width of web materials that can be handled is 60 cm. Figure 1 shows a picture of the practical setup. The machine contains all the main web machine elements to handle and process different types of web materials. Fig. 1 shows in detail an unwinding and winding group to handle the begin and end product, tractions groups for imposing a web speed, dancers for tension control during web transport, load cells to measure the absolute tension and accumulator for buffering web material and creating smooth start/stop processes. The next section briefly outlines the general control principle of the unwinding part. The machine control can be split into a speed and a tension control loop.

III. Web machine speed and tension control

A web material speed setpoint is directly imposed to the traction group (coated yellow roll on Figure 1). The traction is the master. As visualized on Figure 2, the speed imposed to the roller group is based on the web material speed of the adjacent traction group and feedback of the ultrasonic sensor measuring the radius of the web roll. If the web material speed of the traction group is constant, the speed of the roller group has to increase as the radius of the web roll decreases during this process and vice versa.

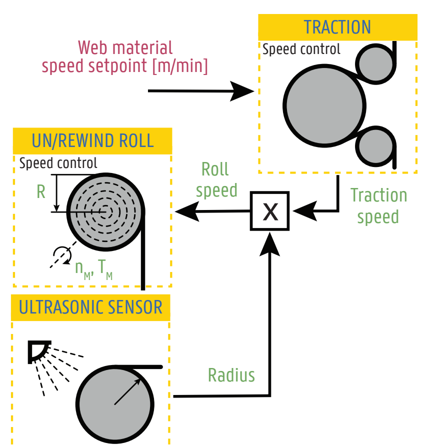

Fig. 2. Web speed control with the traction and (un)winding group

The element that is used to create the tension in the web is the dancer. The dancer can move freely around the center point and touches the web in two places with two free-run rolls. By moving the dancer by means of an external force, the web can be increased or decreased. The external force on the dancer is here applied by a torque-controlled permanent magnet motor. The tension in the web is then equal to the motor torque divided by the dancer crank length. Note that due to the dancer's geometry, this crank length is variable as a function of the dancer angular position (Fig. 3).

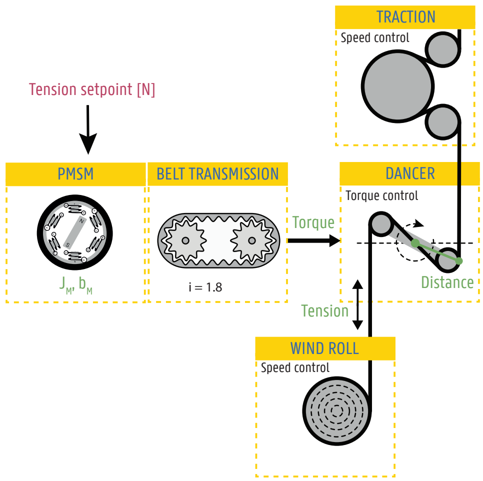

Fig. 3. Web tension control with the dancer

A. Dancer position control

If the web speed of the roller group not exactly matches the web speed of the traction group because of for example an eccentric and non-circular unwind roll or even an inaccurate radius measurement, then the dancer must react as a kind of buffer. By rotating around its axis, the dancer compensates for the shortage or surplus of web material created by the roller of traction group. Of course, the buffer size of the dancer is limited, so the dancer cannot continue to do this. The position range of the dancer is approximately [-50 °, +50 °], where the zero position equals the horizontal line (Fig. 3). To ensure that the position of the dancer remains within the limits during operation, next to speed winding and tension control, an addition dancer position control loop is necessary. For that reason, the speed imposed to the winding group is increased with the output of this controller, as shown in Figure 4. Feedback of an inclinometer enables knowledge of the dancer position and is used to adapt the speed setpoint of the winding group. If the speed of the winding group increases, the tension in the web decreases and the dancer will compensate this by buffering web material. If the speed of the winding group decreases, the tension in the web increases and the dancer will compensate this by releasing web material.

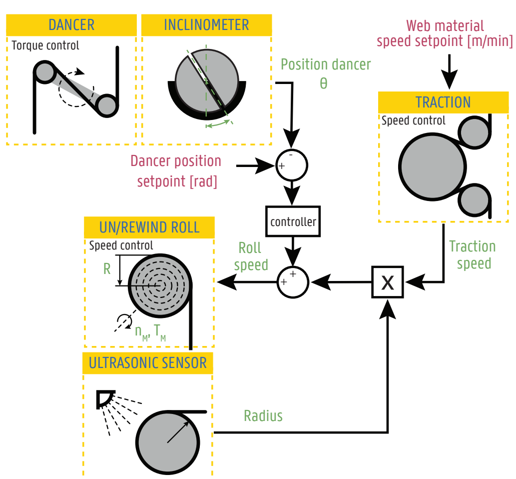

Fig. 4. Closed-loop dancer position control

IV. Web behaviour: linear, viscous and linear-viscous materials

The goal in this paper is to adapt the machine control to the web material behaviour. Web materials can be divided in three classes based on their reaction on stress. Elastic materials stretch when a tension is imposed and immediately return to their original state when the tension is removed. Elasticity is accompanied by temporary deformation. When the deformation is no longer temporary, it is referred to as plastic deformation.

When an elastic material is loaded with a sinusoidal stretch, the stress signal is completely in phase with the stretch signal. The amplitude of the stress signal is independent of the frequency, but completely related to the stiffness. All the energy supplied to the material during loading is completely returned to the environment during unloading. The stretch and destretch follow the same stress-strain path. This is evident, for example, in a spring, which returns to its original length after applying a force.

Viscous materials deform linearly with time when loaded. The definition states that the stress is directly proportional to the applied strain rate. This means that when a viscous material is loaded with a sinusoidal excitation, the stress signal is 90° ahead of the strain signal. The amplitude of the strain signal depends on the damping and the imposed frequency.

Since most web materials are composite materials, they exhibit both elastic and viscous properties when deformed, and can thus be called viscoelastic materials [10], [11]. The web model includes for that reason a stiffness and a damping dependent factor. The web tension F_{w} can be mathematical described with k_{w}, b_{w}, Δx and Δv respectively the stiffness, damping, web extension and web speed difference:

$$F_{\mathrm{w}} = k_{\mathrm{w}}\ \Delta x + b_{\mathrm{w}}\ \Delta v \tag{1}$$

V. Mathematical model of web machine

The above web handling control can be summarized in a model. This model contains the mechanical behavior of the actuators (inertia, damping and external force) and the speed/tension control loops of each actuator.

(1) can be rewritten as:

$$F_{\mathrm{w}} = k_{\mathrm{w}}\ (x_{\mathrm{t}} - x_{\mathrm{r}} - x_{\mathrm{d}}) + b_{\mathrm{w}}\ (v_{\mathrm{t}} - v_{\mathrm{r}} - v_{\mathrm{d}}) \tag{2}$$

With x and subscripts t, r and d indicating respectively the web position of traction, roller and dancer. Transforming the equation above to the frequency domain leads to:

$$F_{\mathrm{w}}(s) \quad = \quad (k_{\mathrm{w}} + s.b_{\mathrm{w}})\left(\frac{v_{\mathrm{t}}(s)}{s} - \frac{v_{\mathrm{r}}(s)}{s} - x_{\mathrm{d}}(s)\right)$$

Transformation from translational to rotational position is done for the dancer by taking into account the dancer geometry.

The dancer buffer factor $z_\mathrm{d}(\theta_\mathrm{d})$ is the transforming factor between dancer position θ_d and dancer web buffer length x_d and is dependent on the dancer position θ_d.

$$F_\mathrm{w}(s) = (k_\mathrm{w} + s\ b_\mathrm{w}) \left(\frac{v_\mathrm{t}(s) - v_\mathrm{r}(s)}{s} - \theta_\mathrm{d}(s)\ z_\mathrm{d}(\theta_\mathrm{d}) \right) \quad (3)$$

The difference in web traction speed v_t and roller speed v_r is the speed level the dancer position controller imposes, as shown in Fig. 4. Finally (3) can be rewritten to dancer position θ_d as a function of the controller speed Δv

$$\theta_\mathrm{d}(s) = \frac{1}{z_\mathrm{d}(\theta_\mathrm{d})} \frac{1}{s} \left(\Delta v(s) + \frac{s\ F_\mathrm{w}(s)}{k_\mathrm{w} + s\ b_\mathrm{w}} \right) \quad (4)$$

Based on the torque equation of the dancer, the web tension can also be written with r_d the crank length of the dancer as:

$$T_\mathrm{d} = J_\mathrm{d}\ \alpha_\mathrm{d} + b_\mathrm{d}\ \omega_\mathrm{d} + 2\ r_\mathrm{d}(\theta_\mathrm{d})\ F_\mathrm{w} \quad (5)$$

Transforming (5) to s-domain:

$$F_\mathrm{w}(s) = \frac{T_\mathrm{d}(s) - J_\mathrm{d}\ \alpha_\mathrm{d}(s) - b_\mathrm{d}\ \omega_\mathrm{d}(s)}{2\ r_\mathrm{d}(\theta_\mathrm{d})} \quad (6)$$

Substituting (6) in (4) leads to:

$$\theta_\mathrm{d}(s) = \frac{1}{z_\mathrm{d}(\theta_\mathrm{d})} \frac{1}{s} \left(\Delta v + \frac{s}{2\ r_\mathrm{d}(\theta_\mathrm{d})} \frac{T_\mathrm{d}(s) - J_\mathrm{d}\ \alpha_\mathrm{d}(s) - b_\mathrm{d}\ \omega_\mathrm{d}(s)}{k_\mathrm{w} + s\ b_\mathrm{w}} \right) \quad (7)$$

Fig. 5 shows formula (7) schematically.

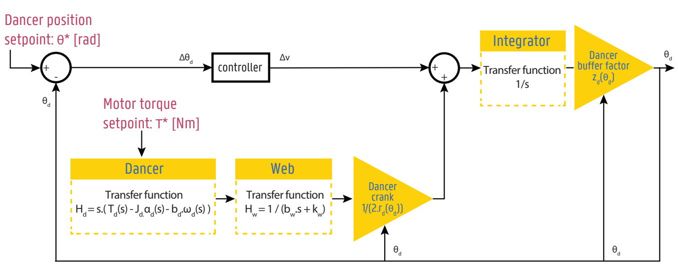

Fig. 5. Closed-loop dancer position control scheme

A. Dancer geometry parameters: buffer factor z_d and crank length r_d

In this section, the actual crank length r_d and the dancer buffer factor z_d are visualized based on the dancer geometry. The outcome is verified with measurements. On Fig. 6, all relevant dimensions are labelled. Symmetry of the dancer setup is assumed. Fig. 7 shows the crank length r_d and the dancer buffer factor z_d as function of the dancer position θ_d.

VI. Web Parameter Estimation

The remaining unknown parameters in (7) are the web stiffness k_w and damping b_w. This paper proposes to perform web parameter estimation by exciting the web utilising the dancer. The dancer is controlled with a permanent magnet motor set in torque mode. A sinusoidal torque excitation with a frequency of 1 Hz is imposed and results in an oscillating dancer at standstill of the web. Position and speed of the dancer are known using the position sensor of the motor.

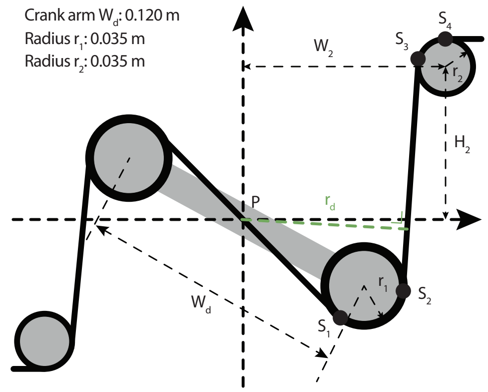

Fig. 6. Dancer geometry

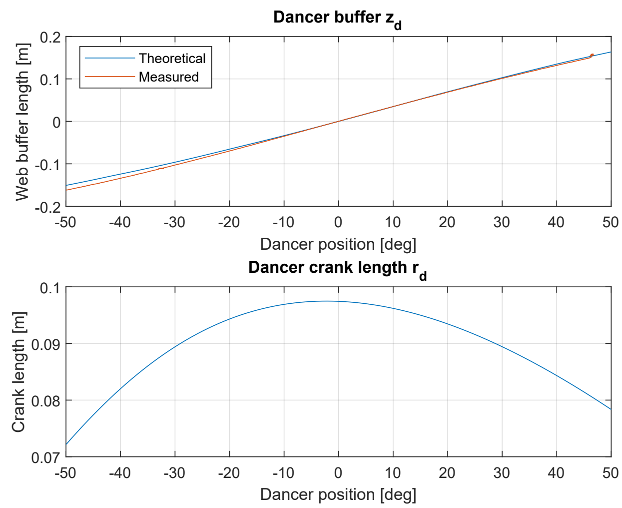

Fig. 7. The crank length r_d and the dancer buffer factor z_d as function of the dancer position

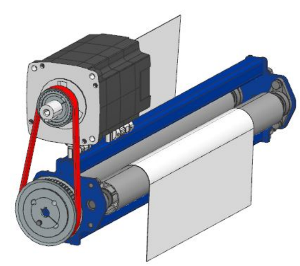

Fig. 8. Dancer control system with permanent magnet motor and toothed belt transmission

In this paper, dancer control behaviour is examined for two web materials, namely wrapping paper and orange kerdi. Kerdi is a sealing mat made of soft polyethylene with a special fleece fabric on both sides. Paper and kerdi are used here as examples for respectively the thin and stiff material and the thicker and more stretchy material. Table I summarizes the material specifications.

TABLE I
WEB MATERIAL SPECIFICATIONS

	Wrapping paper	Orange kerdi
Width [cm]	50	55
Thickness [μm]	90	200
Mass density [g/m^2]	70	150
Structure	glued pulp	three layers
Est. stiffness [N/m]	22500	5500
Est. damping [N/m/s]	50	350

Figure 9 shows the position and speed response on 10 Nm sine-wave torque excitation for the wrapping paper followed by the kerdi. During this simulation, both materials are connected to each other so that when unrolling the web, first the paper is exited with the dancer and then the kerdi. Based on the crank length r_{d} and the buffer factor z_{d} transforming factors (Figure 7), these signals are converted to web tension and web extension.

To extract the desired web parameter information from the response, (1) describing the web dynamics is separated for its real and imaginary parts and used as starting point here:

$$\Re(F_{\mathrm{w}}) = k_{\mathrm{w}}.\Re(\Delta x) + b_{\mathrm{w}}.\Re(\Delta v)$$
$$\Im(F_{\mathrm{w}}) = k_{\mathrm{w}}.\Im(\Delta x) + b_{\mathrm{w}}.\Im(\Delta v) \quad (8)$$

Web stiffness and web damping can then be calculated as follows:

$$k_{\mathrm{w}} = \frac{\Re(F_{\mathrm{w}}) - \frac{\Re(\Delta v).\Im(F_{\mathrm{w}})}{\Im(\Delta v)}}{\Re(\Delta x) - \frac{\Re(\Delta v).\Im(\Delta x)}{\Im(\Delta v)}} \quad (9)$$

$$b_{\mathrm{w}} = \frac{\Im(F_{\mathrm{w}}) - k_{\mathrm{w}}.\Im(\Delta x)}{\Im(\Delta v)} \quad (10)$$

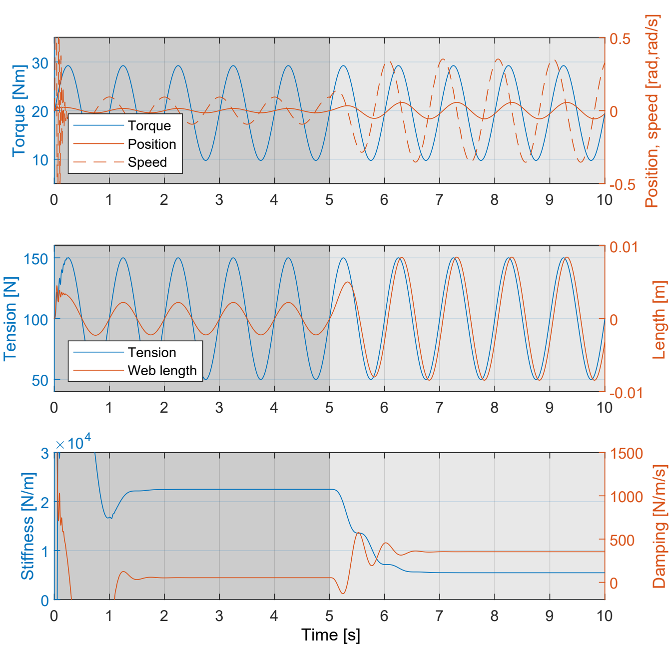

Fig. 9. Simulation results of the dancer response (torque, position and speed), translated to web tension and extension and online web parameter estimation for wrapping paper (0-5s) and orange kerdi (5-10s)

Fourier techniques can be used to determine online the complex representations based on these sampled signals. The real and imaginary part of these signals are here tracked online with a Sliding Discrete Fourier Transformation (SDFT) algorithm [12]. The window length is fixed to the excitation period of 1 Hz. Based on (10), an estimation of the stiffness and damping of the web is obtained, see Figure 9 and Table I.

VII. WEB BASED CONTROL

Identification of the machine and web parameters allows more advanced control. This paper proposes a controller consisting of two parts each with its own specific function, see Figure 10. A simple P-controller should control the web roller speed based on dancer setpoint and current angle so that the dancer position is maintained around zero within the position limits. The feed forward controller has a more important task of controlling the web roller speed so that tension variation-free web speed trajectories can be imposed to the machine.

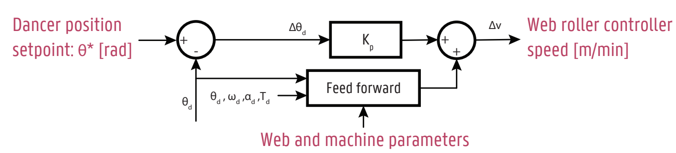

Fig. 10. Proportional dancer control with feed forward loop

A. P-controller

The K_{p} factor of the P-controller is set according to the total response of the machine (7). Fig. 11 shows the reponse $H = \frac{\theta_{\mathrm{d}}}{\Delta v}$ for the machine with wrapping paper and kerdi. Since the goal is to control the dancer so that there is as little tension variation in the web as possible, it is chosen to set the P-controller robust and thus less active. Here, the P-controller is adapted based on (7) after each new web parameter estimation so that the phase margin is 45°.

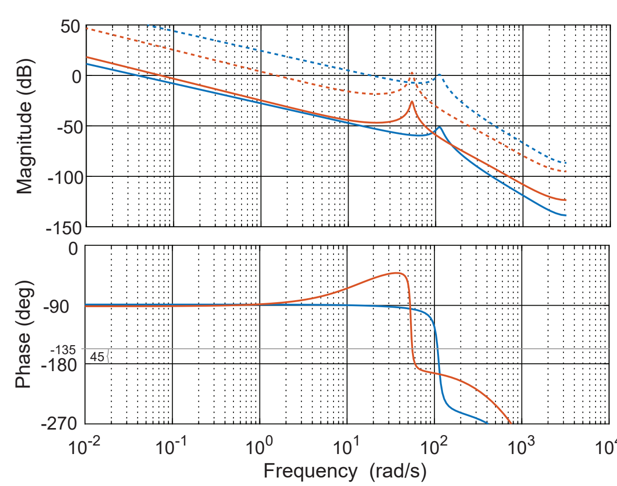

Fig. 11. Bode response of the web processing machine for web material paper (blue) and kerdi (orange) - full lines, controller tuned response (dotted line)

B. Feed forward

In this section, a feed forward controller is defined which bypasses the P-controller dynamics and ensures tension variation-free web speed transport. Based on (4), the feed forward loop can be set up. The feed forward level can be calculated based on the measured dancer signals, the machine parameters and the estimated web parameters:

$$\Delta v(s) = \qquad (11)$$
$$z_\mathrm{d}(\theta_\mathrm{d}).s.\theta_\mathrm{d} - \frac{s}{2.r_\mathrm{d}(\theta_\mathrm{d})}.\frac{T_\mathrm{d}(s) - J_\mathrm{d}.\alpha_\mathrm{d}(s) - b_\mathrm{d}.\omega_\mathrm{d}(s)}{k_\mathrm{w} + s.b_\mathrm{w}}$$

Figure 12 shows the final simulation result of the feed forward proportional dancer controller for a web speed step and s-curve stop trajectory. At 30 s and 35 s, respectively a step speed variation from 30 to 40 $\mathrm{m\,min^{-1}}$ and 0.2 s s-curve stop trajectory is imposed. As can be seen, the dancer position is steadily controlled to zero position. With or without feed forward, the settling time is here around 2.5 s. More important is the impact of the feed forward loop on the web tension variation. For the web speed step, a sharp tension spike occurs both with and without feed forward. However, with feed forward, the transient is nullified much faster. In practice, because of the stress peaks, step-shaped trajectories are not imposed. Hence the s-curve shaped stop trajectory. The tension spike cannot be seen here and with feed forward there is hardly any tension variation.

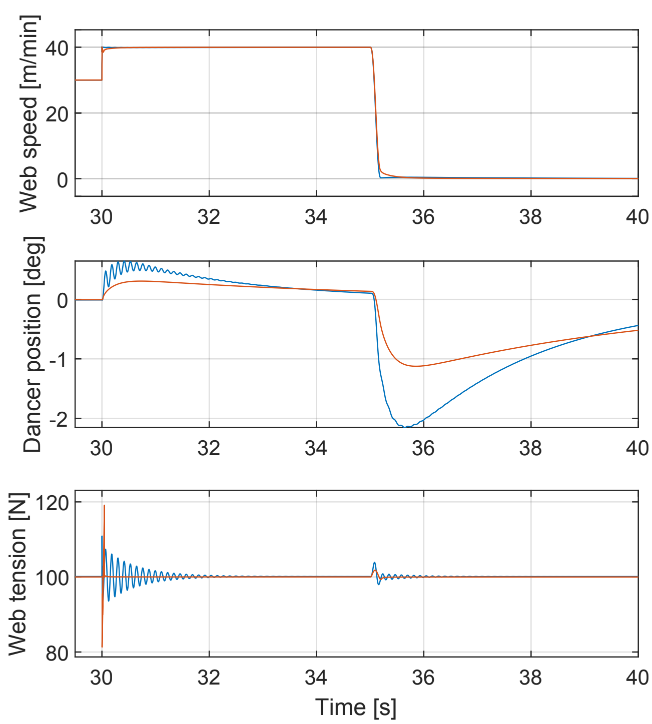

Fig. 12. Web speed, tension and dancer position response for step and s-curved web speed transient with (orange) and without (blue) feed forward

VIII. Conclusion

As the web is the linkage between all the actuators, knowing the physical parameters of the web will help increase web dancer control. In this paper, a virtual model of a web winding machine is presented. A signal injection based method is proposed to estimate the physical parameters of the web. A sine-wave tension excitation is imposed to the web, analysing this tension trajectory and the resulting web extension using Sliding Discrete Fourier Transformation (SDFT) results in a web stiffness and damping estimation. Identification of the machine and web parameters allows more advanced control. This paper shows simulation results of a dancer controller consisting of two loops, each with its own specific function. A P-controller should control the web roller speed based on dancer setpoint and current angle so that the dancer position is maintained around zero within the position limits. The feed forward controller has a more important task of controlling the web roller speed so that tension variation-free web speed trajectories can be imposed to the machine. In the expended paper version, experimental results and controller stability analysis will be provided.

Acknowledgment

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