Title:

LOW COST VACUUM WEB COATING SYSTEM

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Abstract:

A low cost solution for a mini roll to roll web coating system is presented. The design is very simple and involves only three active rolls, two winding/unwinding rolls and a cooling drum. No extra load cells are used to control the web winding mechanism operation. To reach such result it has been necessary to develop an adequate control solution which acts on the two winding roll torques to make the web moving properly. The effect of the control mechanism is to increase electronically the total mechanical inertia of the roll to roll system. In such manner the stick-slip motion of the web, induced by the dry friction affecting the rotation of the rolls, is avoided. The effectiveness of this strategy has been corroborated: a first test showed that the web moves continuously while it is kept tense; in a second experiment a-Si material has been deposited by hot-wire chemical vapor deposition technique. For that material the optical transmission measurements at several points over the deposited area indicate a satisfactory uniformity. The presented tests validate the goodness of the new control method.

Keywords: Vacuum technology, roll to roll system, flexible substrate and cooling drum.

1. Introduction

Roll to Roll (R2R) processing is a manufacturing technique for continuously depositing material on a flexible substrate. In the simplest R2R systems the flexible substrate is placed on an unwinding roll, from which is unwound to enter in a processing area. The material is deposited and the coated film leaves the deposition area to be wound on a rewinding roll. From simpler R2R coating apparatus to much more complex onto web coating systems for industrial purposes have been developed during the last three decades [1-6]. In many coating web processes the substrate at deposition area needs to be cooled to evacuate the heat generated during the deposition. The generated heat at the deposition area is evacuated using a cooling drum as a deposition drum. The web has to be kept tense over the drum to make the cooling process effective. The common strategy to control the web tension is to use two additional rolls acting as load cells placed between the two winding/unwinding rolls and the cooling drum [7]. The load cells are used as force sensors to measure the local tension of the web. Their signals are fed back to servo amplifiers to adjust the motors, or the brakes torque acting on the winding/unwinding rolls in such a way that the web is kept independently to the external perturbations.

Moreover the proposed system is for scrolling velocity in the order of centimeter per minute. Without an adequate control based on load cells, at this speed regime, external perturbations like dry and viscous frictions can affect the tension of the web. Moreover at high web tension the axes of the rolls undergo high radial forces which make the existence of dry friction even more significant as explained by the Coulomb model. As it will be showed in this paper, an important dry friction can also determine stick-slip velocity profile. This phenomenon is well known to affect machine with strong dry friction, and its suppression can be difficult [8, 9].

The purpose of this paper is to show that for R2R processing with winding speed, less than 10 cm/min, the system can be controlled without using any load cell, just increasing electronically the total inertia of the system. In that case, problems due to the presence of external and non-linear torques are overcome and it is showed that the web is kept tense while moving continuously at a constant velocity. To experimentally test the goodness of this solution it has been used in a mini R2R system fabricated at the Universitat de Barcelona.

The paper is organized as follows: firstly, the mini R2R system is described and the design principle based on the electronic increasing of the total inertia is mathematically explained. Secondly the web motion at low velocity is studied experimentally. Thirdly, amorphous silicon has been deposited by hot-wire chemical vapor deposition (HWCVD) on PEN substrate to prove the effectiveness of the system in evacuating heat irradiated by the filaments and to test the uniformity of the deposited material.

2. Characteristics and design basics of the mini R2R system

The mini R2R mechanical assembly is shown in Figure 1. The system has been thought as laboratory multipurpose R2R system for vacuum coating over 10 cm width webs. The mini R2R is composed of two interchangeable unwinding/rewinding rolls and a cooled deposition drum. In the picture the small rolls are the interchangeable rewinding/unwinding rolls, and the central roll is the cooling drum. DC brushless motors fed by servo amplifiers are used to drive the rolls. The system is very compact and the three rolls were loaded inside a cubic vacuum chamber with a side length of 40 cm as showed in the picture. The system part that stands outside the chamber includes DC motors, connection shafts, gear boxes and belts. For the cooling drum the shaft is connected to the external rotating system via an O-ring shape feed-through providing hermetic sealing. Concerning the winding rolls, the roll is connected to the motor shaft by a damper and the mechanical arm is fed from the outside by a magnetic feedthrough.

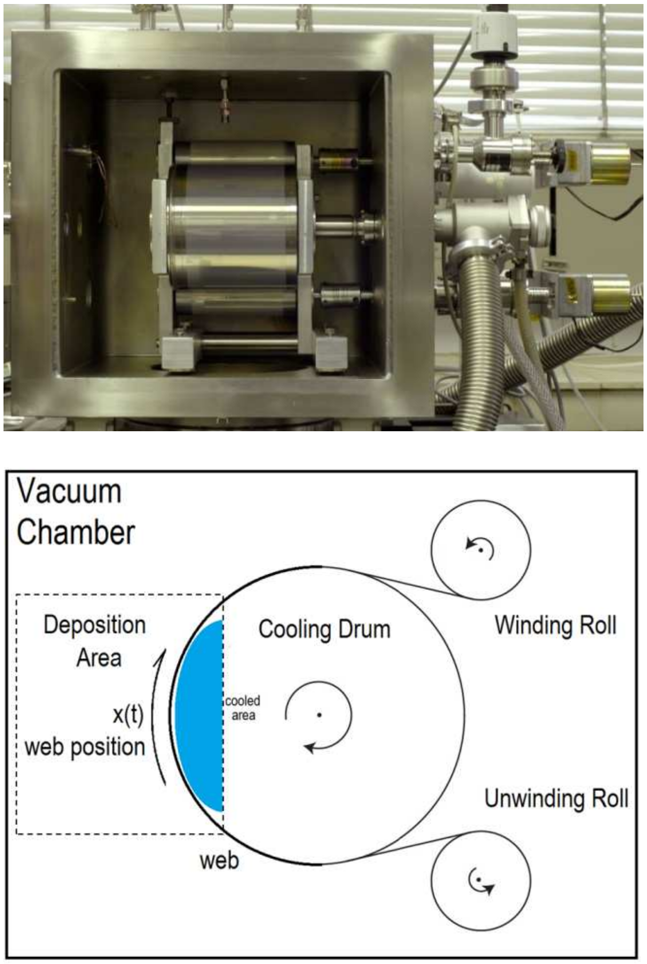


Figure 1. Picture of the Roll to Roll system fabricated at the Universitat de Barcelona (top). 2-D Scheme of the mini Roll to Roll system inside the vacuum chamber (bottom).

In the case of R2R systems composed of only three active rolls the controls of the web velocity and the web tension can be easily decoupled. In our design the web speed is fixed by the rotation of the central cooling drum which is driven by a velocity controlled motor. On the other hand, the web is maintained in tension over the cooling drum controlling the torques supplied, by the two DC motors, to the winding and unwinding rolls. The torque applied to the unwinding roll is acting in the opposite direction respect to its rotation and it makes the motor working as a break. In an ideal system, without any dry and viscous frictions, any supplementary load cell rolls would not be necessary to control and keep tense the web. However, as already mentioned in the introduction, this is not the case as in real systems. Figure 2 shows the simplest realistic model we will use here to explain the behavior and then justify the design of our R2R system without load cells.

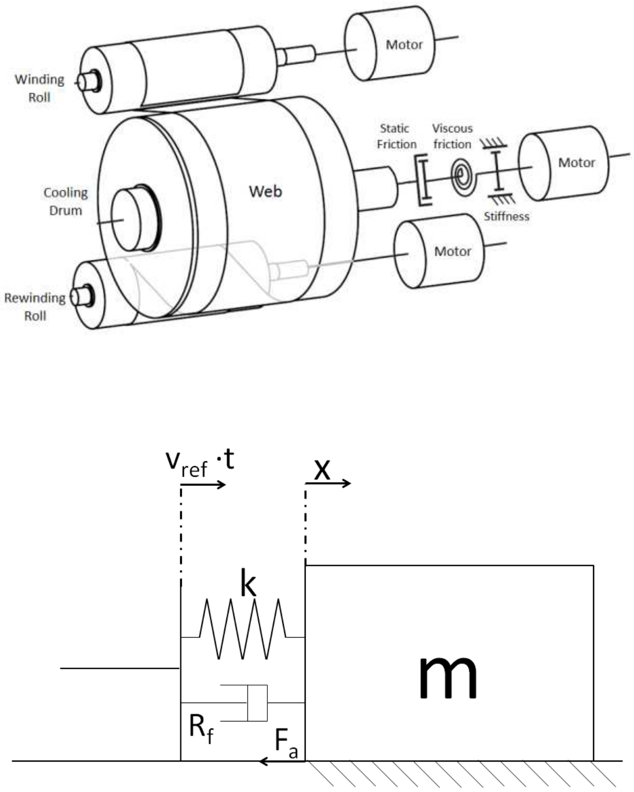


Figure 2 –System rotational motion model (top).

System linear motion model (bottom).

The three rolls are coupled together by means of the tensed web and they are considered as a single rigid rotating system characterized by a total rotating inertia

$$I_{tot} = I_c + \frac{2R_c}{R_{W/R}} I_{W/R} \qquad (1)$$

where I_c and $I_{W/R}$ are the rotational inertias of the cooling drum, and of the winding/unwinding rolls, respectively. $R_c/R_{W/R}$ is the ratio between their radii. The inertia $I_{W/R}$ includes also the inertia of the two DC motors rotors connected to the winding/unwinding rolls. All internal degree of freedom of the R2R are not considered here. Since it is interesting to study the web position $x(t)$ and not its rotation around the cooling drum axis, the total mass $m = I_{tot}/{R_c}^2$ is introduced to describe the system as a linear motion system, like the one sketched in Figure 2 at the bottom.

The coupling between the rotating body and the cooling drum motor controlled in velocity mode is affected by a viscous friction, which can be expressed in the linear motion model by a friction resistance R_f. The stiffness of the coupling has also to be taken into account introducing in the translational system a spring with k as force constant. One end of the spring is connected to the total mass m, while the other end is forced to move at a constant velocity v_{ref}.

Since v_{ref} is very low, the dry friction plays an important role in determining the behavior of the web movement. To start moving the spring has to be compressed to overcome the static limit friction force F_{lim}. This takes a time $t_1 = F_{lim}/k\, v_{ref}$. After this lapse of time, the value of the dry friction drops suddenly by a value F_a, by switching from a static to a dynamic regime.

The evolution of the web position $x(t)$ starting from this moment is governed by the following equation of movement

$$m\ddot{x} + R_f\dot{x} + kx = kv_{ref}t + F_a. \qquad (2)$$

With the initial condition $x(0) = 0$ and $\dot{x}(0) = 0$. That means the web start moving with an acceleration $\ddot{x}(0) = F_a/m$.

In case of small inertia m the acceleration can be very high. Looking at the general solution, it is found that this generates a damped oscillation superposed to the forced uniform linear motion $v_{ref}t$

$$x(t) = -\frac{F_b}{k}\sqrt{1 + tan^2\varphi}\,e^{-\frac{R_f}{2m}t}cos(\omega t - \varphi) + \frac{F_b}{k} + v_{ref}t \qquad (3)$$

where F_b, ω, and $\tan\varphi$ are respectively:

$$F_b = F_a - R_f v_{ref}; \qquad \omega = \sqrt{\frac{k}{m}}; \qquad \tan\varphi = \frac{\frac{kv_{ref}}{F_b} + \frac{R_f}{2m}}{\sqrt{\frac{k}{m} - \frac{R_f^2}{4m^2}}}.$$

F_b is considered in our case always positive due to the very low web velocity which we would like to control. The interesting behavior of the system comes out studying the velocity as a function of the mass (inertia) of the system.

Starting from equation 3 it is easy to show the velocity amplitude of the free oscillation part, for small inertia m, is proportional to the angular frequency ω of the oscillation, which increases when the mass of the system decreases. That means for sufficiently small inertia the strong initial acceleration induces a rapid, large oscillation superposed to the velocity v_{ref}. The velocity goes to zero after about half oscillation $t_2 = \pi\sqrt{m/k}$. Neglecting the damps of the viscous friction, in this short lapse of time the web moves forward of about $x_2 = 2\,F_b/k$. For small inertia this can be much more than the distance the web would go on moving at constant velocity v_{ref} during the same lapse of time, i.e. $v_{ref}\,\pi\sqrt{m/k}$. Thereafter the web stops due to the static friction. The web is motionless until the speed controlled motor, moving at the velocity v_{ref}, compresses sufficiently the spring to overcome the static limit friction force F_{lim}. This takes about $t_3 = 2\,F_b/(k\,v_{ref})$. The movement cycle is ready to restart with another jump. This describes the movement of the web for too low inertia is of the stick-slip type.

Let us now see what happens in system with large inertia m. In this case, the system is subject only to a small initial acceleration induced by the dry friction. The velocity amplitude of the free oscillation reaches for large m an asymptotic value $\sqrt{\left({v_{ref}}^2 + {F_b}^2/(k\,m)\right)}$, which is superposed to the velocity v_{ref}. The period of the free oscillation becomes very large. Without any viscous friction the web would stop after a lapse of time larger than $t_2 = \pi\sqrt{m/k}$. However, the presence of the damping can reduce the amplitude of the oscillation and that makes the velocity never going to zero. In this last case the web can move continuously reaching after a transitory time the stationary velocity v_{ref}. The estimation of the critical inertia value m_c, which separates the stick-slip regime from the continuous one is not easy to carry out. However, an overestimation of its value for the case of weak damped system led to the result,

$$m_c < \frac{1}{\pi^2}\frac{1}{{R_f}^2 k}\left(\frac{F_b}{v_{ref}}\right)^4. \qquad (4)$$

The model introduced above let us show, why the inauspicious stick-slip phenomenon, which affects the web motion at low velocity, can be avoided just increasing sufficiently the total inertia of the R2R. To increase the total inertia the winding/unwinding rolls motion is controlled by the enhanced torque mode block which is outlined in detail in the right sketch of the figure 3.

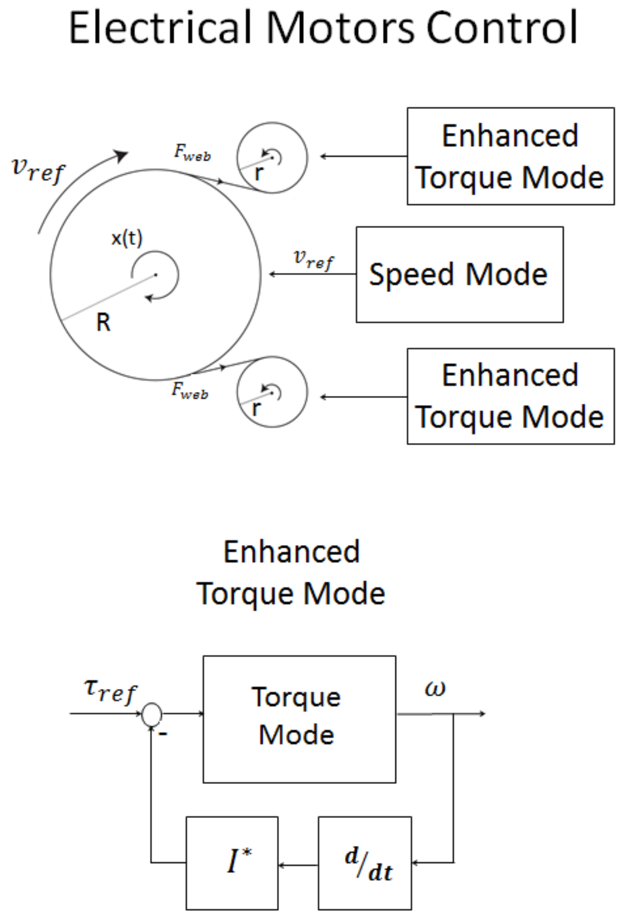


Figure 3 - A schematic of the three rolls system with the electrical motors control (top). Feedback detail of the Enhanced Torque Mode block (bottom).

The block of the enhanced torque mode is composed of a DC motor driver in current mode control to set the mechanical torque and an electronic inertia feedback with a gain I^*. In this way, the total lineal inertia m characterizing the R2R system can be increased. In fact, now

$$m = \frac{I_c}{{R_c}^2} + \frac{2}{R_{W/R} \cdot R_c}(I_{W/R} + I^*) \qquad (5).$$

The increasing of the gain I^*, in terms of real effects, makes m becoming larger than the critical inertia m_c. It allows overcoming the stick-slip motion of the web, and entering in the continuous regime.

3. **Results and discussion.**

3.1. **The web motion at low velocity.**

Measurements of the angular velocity ω were performed in order to test the system behavior. The position profile $x(t)$ was obtained from the angular velocity. Two relative position profiles for the velocity v_{ref} = 45mm/min, which are descriptive of the system motion regimes at low velocity are drawn in the following plot in figure 4.

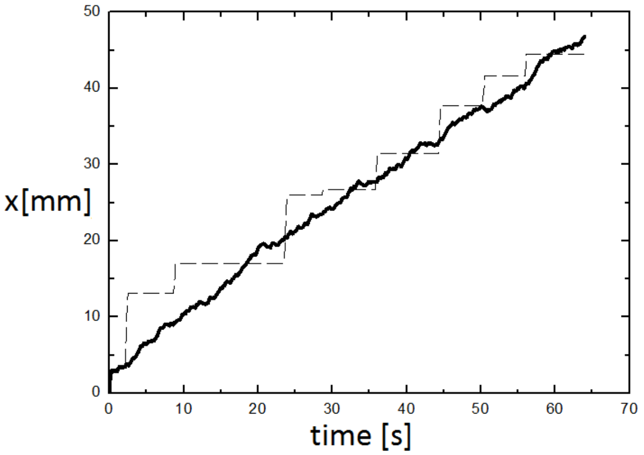


Figure 4 - Web position profile for two values of the electronic inertia gain $I^* = 0$ (dashed line) and $I^* > I_{cr}$ (solid line).

The dashed line shows the position profile for I^* =0, that is when the control would be a mere feed-forward control. In this case, the total linear inertia m corresponds to the raw mechanical, which can be calculated using equation 5. For our mini R2R, m was about 15 kg. The web motion in this case was affected by the stick-slip phenomenon. The position profile showed horizontal plateaus where the R2R is motionless. During this period, which can vary between 7 and 15 s, the web did not move, the dry friction was sticking the system in its position. The central cooling drum motor was in any case advancing at the constant velocity v_{ref} until the coupling stiffness is employing a force higher than the static limit. At that moment the friction dropped and the web rapidly slipped. The period of the slipping phase was much shorter than the sticking one, and was included in the range between 0.3 and 0.6 s. The times characterizing the sticking and the slipping phases have been introduced in the previous section and are t_3 and

t_2, respectively. Their values made it possible to estimate the force constant k and the force drop F_b of our system

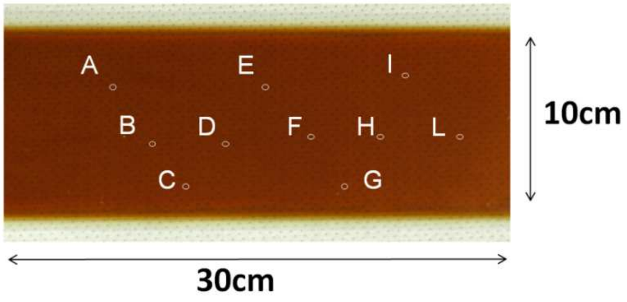
$$k = \frac{\pi^2 m}{t_2} \approx 4\frac{N}{mm} - 0.4\frac{N}{mm} \qquad\qquad F_b = \frac{t_3\, k\, v_{ref}}{2} \approx 20N - 1N.$$

The variation of F_b is probably a result of many causes. Such as from distorted cores and so lobed rolls, or may be due to the blocking of the unwind roll due to either migration of oligomer to the surface coupled to a high roll tension or too much residual static on the roll both of which can cause the unwind roll to stick and unwind unevenly. To give an idea of which kind of perturbation this could induce in the tension of our web, the force applied to the web to tense it over the cooling drum was about 120 N on the size of the winding roll, and 60 N on the size of the unwinding roll. However, these forces were internal to the system and, with our simple model, we were not able to say how they were influenced by the force drop F_b.

The solid line in figure 4 shows the position profile for I^* = 120 $Kg \cdot m^2$. In this case, the total linear inertia was augmented electronically of about 1000 times compared with its initial mechanical raw value. The motion was not anymore affected by the slip-stick phenomenon and this time the position profile showed the web was moving uniformly. The value of the electronic inertia gain let the total mass of the system to be higher than the critical inertia value m_c. Discontinuous position profiles are unwanted so the choice of feedback control is necessary.

3.2 Deposited material onto flexible substrate.

The winding R2R system was used to deposit hydrogenated amorphous silicon thin film onto PEN foil (Teonex Q83 0.05 mm thick). HWCVD was used as deposition process technique [10]. Two tungsten wire holding system was mounted at the deposition area. 0.3 mm diameter W filaments were used, at wire current I = 18 A and voltage V =17 V, and the filament temperature was calculated to be T_{fil} = 2000°C. The filaments were encapsulated in a confinement box which had an aperture window of 7 cm × 10 cm in correspondence of the deposition area. A silane flow Φ_{SiH_4} = 5 sccm and a deposition pressure p_{dep} = 0.01 mbar were chosen as deposition parameters. The web velocity was fixed at a reference value v_{ref} = 100 mm/min and the material was deposited along a 30 cm length web.



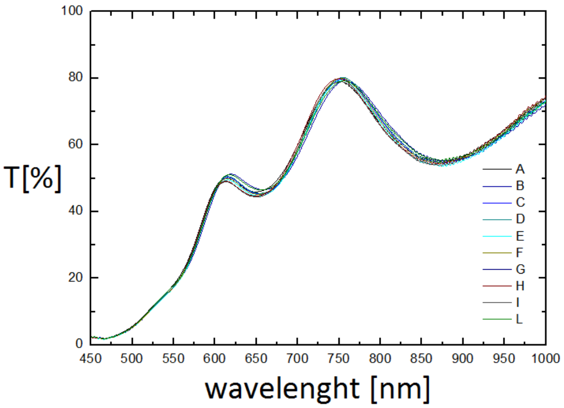


Figure 5 - a-Si:H deposited on a 10 cm × 30 cm PEN substrate. Points (A, B, C, D, E, F, G, H, I and L) circled in the picture indicate the area where it has been measured the optical transmittance (top). Optical transmittance spectra for the points distributed over the deposited area (bottom).

The deposited material on PEN substrate as the final product is shown in the picture in figure 5. Optical transmittance with UV-VIS_NIR spectrophotometer *PerkinElmer Lambda 950* was measured for several points distributed over the deposited material surface (points A, B, C, D, E, F, G, H, I and L). The results are showed in the plot in figure 5. For all points, the transmittance spectra were very similar. This means the thickness and the optical constants characterizing the deposited amorphous silicon were very uniform [11]. The goodness of the system operation in terms of heat evacuation and constant web motion at the deposition area gave as a result a good uniformity for the deposited material.

4. Conclusions.

A low cost R2R winding system with a cooling drum for vacuum application with only three rolls has been designed and fabricated. High forces are necessary to keep tense the web over the cooling drum, in such a way the heat evacuated from the substrate during the deposition is effective. Unfortunately, the high web tension makes the rolls axes undergo high radial forces, which induces the increase of dry frictions. It has been showed how this kind of friction is connected to the stick-slip motion of the web at low displacement velocity. This unwanted phenomenon has been eliminated without the use of load cells. An electronic control method has been introduced in the winding/unwinding motors to increase electronically the total inertia of the system. This suppresses the discontinuity in the web position profile making the web move continuously also at the extremely low web velocity of only 45 mm/min. The functionality of R2R system has been tested depositing amorphous silicon by HWCVD. The results show a good uniformity of the deposited material. The filament high power irradiated by the filaments (300 W) does not compromise the integrity of PEN substrate validating the proper system operation.

Acknowledgements

This research has been supported by the Spanish Ministry of Science and Innovation and the European Regional Development Fund through the projects AMIC (ENE2010-21384-C4-03) and HELLO (ENE2013-48629-C4-2-R).

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