Modelling and Control of Roll-to-Roll Systems

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Outline

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2. 1D Web dynamics model
   - Modelling
   - Influence of parameter variations in open-loop

3. Control of Roll-to-Roll systems
   - Influence of parameter variations in closed-loop

4. Influence of the tension and velocity closed loop bandwidths

5. 3D Web dynamics with finite element modelling

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Problem formulation: 1D modelling

Most models in roll-to-roll systems are one-dimensional:

- Give the average tension in each web span and the velocity of each roller
- Short simulation time
- They do not take into account lateral or cross-machine effects
- Assuming no slippage between web and roller
- They are not able to predict/analyze web wrinkles

Longitudinal web dynamics modelling: simulator in Matlab/Simulink
Problem formulation : 1D modelling

- **1D models** : useful for the controller adjusting/optimization :

- Multi motors nonlinear **simulators**, parameters identification

- Web **vibrations** measurement (load cells, laser, image processing ) and analysis
Problem formulation: 1D modelling

- **Non-circularity** of rollers, unwind- wind- rolls: robust web tension disturbances cancellation -> plug in controller

\[
T_u = \frac{T_2 + T_3}{2}
\]

Controller

Adap_fun

\(e\)

\(\Omega_c\)

\(U_d\)

\(U_u\)

Tension spectrogram with disturbances cancellation controller (on the unwinder)
Problem formulation: 1D modelling

- Web / roller friction modeling and measurements:

- Calculation of the optimal tension and nip load, using wound internal stresses models:
Modelling of Roll-to-Roll systems

- Web speed of the $k^{th}$ roller (assuming no slippage):
  \[ J_k \frac{dV_k}{dt} = R_k^2 (T_k - T_{k-1}) + C_m - C_f \]

- Web strain between two consecutive rollers:
  \[ L_k \frac{d}{dt} \left( \frac{1}{1 + \varepsilon_k} \right) = \frac{V_k}{1 + \varepsilon_{k-1}} - \frac{V_{k+1}}{1 + \varepsilon_k} \]

- Linearization of the tension equation around a working point $T_0 \ v_0$:
  \[ L_k \frac{dT_k}{dt} = (ES + T_0) (V_{k+1} - V_k) + V_0 (T_{k-1} - T_k) \]
Modelling of Roll-to-Roll systems

- Downstream web tension control

\[
\begin{align*}
\Omega_t &= \begin{pmatrix} R_t^{-1} & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0.5 \end{pmatrix} \begin{pmatrix} V_t \\ T_1 \\ V_c \\ T_2 \end{pmatrix} \\
\end{align*}
\]
Influence of parameter variations in open-loop
Influence of the web elasticity in open-loop

- When Young modulus increases:
  - The resonance peaks are moved to higher frequencies
  - The gain of these peaks are amplified
Influence of the web velocity in open-loop

• When web velocity increases:
  • The oscillations decrease
  • The frequencies of the peaks are not affected
Influence of wound roll radii in open-loop

- When radii are varying (unwinder and rewinder): the static gain of the open-loop dynamic varies
Control of Roll-to-Roll Systems
Roll-to-Roll : control synthesis

**Control** : web tension, dancer position, web velocity, register control, accumulator, ...

Cascading control (torque, speed, web tension/dancer angle)  
Measurements : dancer angle control
Roll-to-Roll : control synthesis

- **1D models** : useful for the controller adjusting/optimization
- Automatic synthesis of fixed order and structure **controllers** (PID) :
  - robustness to web elasticity variations
  - effects of closed loop bandwidths ?
  - master roller location ?

- Tension control ($C_t$ : PI controller) or dancer position control :
  automatically optimized with “robust control methodologies”
Roll-to-Roll : control synthesis

- Speed control ($C_v$ : IP controller : does not introduce a zero in the closed-loop transfer function)

- Tension control ($C_t$ : PI controller)
Roll-to-Roll : automatic optimized control synthesis

- **Controller** $C_T$ is automatically optimized (Matlab)
- $M_0$: desired closed loop model (fix the tension-loop bandwidth)
- $W_p$, $W_u$, $W_t$: frequency filters
Robust control: $H_\infty$ approach

- Reminder on the $H_\infty$ controller synthesis
  - Require a system model: linear model
  - Can take into account uncertainties of parameters
  - Well integrated in an optimization strategy

The $H_\infty$ norm is the maximum of the maximum singular values of a system

![Diagram showing the $H_\infty$ norm with a graph plotting gain (dB) against frequency (rad/sec).]
Influence of parameter variations in closed-loop
Influence of web elasticity : frequency domain

- When Young modulus of the web increases :
  - imaginary part of the poles increases
  - many poles are moved to the right and some of them become unstable
Influence of web velocity: frequency domain

- When web velocity decreases
  - Imaginary part of the poles increases
  - Many poles are moved to the right and some of them become unstable
Stability area

\[ E_0 = ES + T_0 \]
Problem formulation

- Roll-to-Roll systems usually contain a large number of actuators
  - The tension control requires an adequate position of the master roller
  - The master roller imposes the web speed of the processing line
  - The other actuators ensure web tension control

Problem statement:

- Where should be the optimal master roller position, in order to respect the system requirements? -> Frechard J, D. Knittel, Drive requirements for elastic roll-to-roll systems, Mechanism and Machine Theory, Elsevier, volume 66, 2013, pages 14-31

- Influence of the tension and velocity closed loop bandwidths?
- How can we obtain a larger closed-loop stability area?
A dedicated system model has been developed for this study

- 7 driven rollers, 6 idle rollers having load cells

**Inputs:**
- $u_i$: Control signal of the driven roller
- $T_{in}$: Web tension at system entrance
- $V_{out}$: Web speed at system exit
- $T_{out}$: Web tension at system exit

**Outputs:**
- $T_i$: Web tensions
- $\Omega_i$: Driven roller rotational speed
Influence of the tension and velocity closed loop bandwidths
A lower bandwidth of the speed loop filters the tension reference variation.
Frequency domain comparison

- Bode diagram of the closed loop system

- With lower crossover frequency of speed loop the maximum singular value is lower
Time domain comparison

- **Web tension**: for closed loop tension bandwidth 5 rad/s and $E_{nom}$

  - **Velocity bandwidth**: 15 rad/s
  - 30 rad/s
  - 50 rad/s

- For $E_{nom} / 100$:
Time domain comparison

- **Web tension**: for closed loop velocity bandwidth 30 rad/s and $E_{\text{nom}}$

- **Tension bandwidth**: 5 rad/s

- **For $E_{\text{nom}}/100$**:

  - 15 rad/s
Influence of the tension and velocity closed loop bandwidths

- Tension and velocity closed loop bandwidths have to be chosen carefully:
  - tension bandwidth < velocity bandwidth
  - robustness to web elasticity variations : reduced velocity bandwidth
How can we obtain a larger closed-loop stability area?
To increase the stability area: LPV control

2 parameters are varying:
- the coefficient $E_0 = ES + T_0$
- the nominal speed $V_0$

Controllers interpolation (example with 2 parameters)

\[
C(\theta) = \sum_{i=1}^{N} \alpha_i C_i = \sum_{i=1}^{N} \alpha_i \begin{bmatrix} \hat{A}_i \\ \hat{C}_i \\ \hat{B}_i \\ \hat{D}_i \end{bmatrix}
\]

with $\sum_{i=1}^{N} \alpha_i = 1$

$\alpha_i$, $i = 1, \ldots, 4$, depend on $\kappa_j$

\[
\kappa_j = \frac{\theta_j - \theta_j}{\theta_j - \theta_j}, \quad j = 1, 2
\]
To increase the stability area: LPV control

2 parameters are varying:
- the coefficient $E_0 = ES + T_0$
- the nominal speed $V_0$
3D web dynamics, using finite element modelling

(controller synthesis with 1D models)
Comparison: 1D models - 3D models

With the same controller: controller parameters calculated with the 1D model
Simulations: 1D and 3D models

- Comparison 1D – 3D (in closed loop: with controllers):
  Co-simulation RecurDyn – Matlab/Simulink
Simulations: 1D and 3D models

- 1D and 3D models:
  - 1D model
  - 3D model

- Comparison 1D – 3D (in closed loop: with controllers):
  - Web tension
  - FEM Results - Lateral Stress and wrinkles
More complex processing lines have been studied: Modeling, analysis and control of complex industrial roll-to-roll plants (confidential works)

processing line with lateral guide: web stresses
Results

Starting phase: velocity slippage roller 3 / web:

![Graph showing slip rate over time]

- $V_{out} f=0.3$
- $V_{out} f=0.5$
- $V_{out} f=1$
Which parameters influence wrinkles?

- Tension: 700 N/m
- Misalignment angle: 0.5 degree
- Friction ratio: 0.5
- Wrap angle: 90 degrees
- Web length/width ratio: 0.2

- medium average stresses value
- High localized stresses (sign of wrinkles)
- Not uniformly distributed stresses across the width
Conclusion

- **The 1D model**
  - **Advantages:**
    - Efficient and sufficient for a lot of applications
    - Automated control synthesis
    - Studies in the frequency domain
    - Fast time simulations
  - **Drawbacks:**
    - Inaccurate web/roller contact
    - Only longitudinal studies

- **The 3D model**
  - **Advantages:**
    - Accurate web/roller contact
    - Large possibility of studies: Complex phenomena such as wrinkles, edge waves, etc.
    - Give us a lot of information about the web: state of stresses
  - **Drawbacks:**
    - Slow time simulations
    - Need adequate tuning (boundary conditions, elements, contact, algorithm)