ROBUST CONTROL WITH YOULA PARAMETRIZATION OF YEAST FED-BATCH CULTURES

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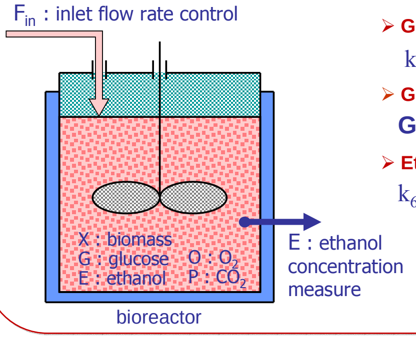
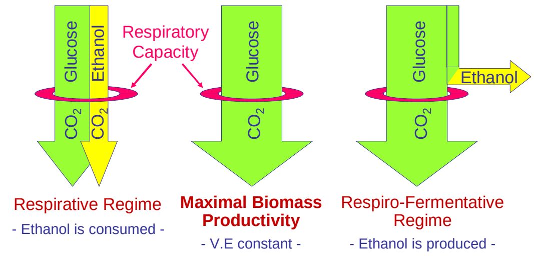
INTRODUCTION

Process description



- **Glucose oxidation**
  $k_5\,O + G \xrightarrow{r_1} k_1\,X + k_7\,P$
- **Glucose fermentation**
  $G \xrightarrow{r_2} k_2\,X + k_4\,E + k_8\,P$
- **Ethanol oxidation**
  $k_6\,O + E \xrightarrow{r_3} k_3\,X + k_9\,P$

Yeast has a limited respiratory capacity



Sub-optimal control strategy consists in controlling E at a low value.

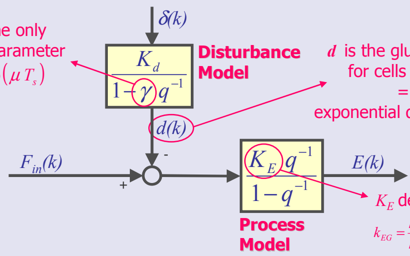
MODELING YEAST FED-BATCH CULTURES

Classical nonlinear model

$$\begin{bmatrix}\dot X\\ \dot G\\ \dot E\\ \dot O\\ \dot P\end{bmatrix}=\begin{bmatrix}k_1 & k_2 & k_3\\ -1 & -1 & 0\\ 0 & k_4 & -1\\ -k_5 & 0 & -k_6\\ k_7 & k_8 & k_9\end{bmatrix}\cdot\begin{bmatrix}r_1\cdot X\\ r_2\cdot X\\ r_3\cdot X\end{bmatrix}-D\cdot\begin{bmatrix}X\\ G\\ E\\ O\\ P\end{bmatrix}+\begin{bmatrix}0\\ G_{in}\cdot D\\ 0\\ OTR\\ 0\end{bmatrix}-\begin{bmatrix}0\\ 0\\ 0\\ 0\\ CTR\end{bmatrix}$$

- ✓ $D = F_{in}/V$: dilution rate;
- ✓ G_{in} : glucose concentration in the feed medium;
- ✓ OTR : oxygen transfer rate;
- ✓ CTR : carbon dioxide transfer rate;
- ✓ $\mu = \sum_{i=1}^{3} k_i r_i$: specific growth rate of biomass.

Suggested linear model for control



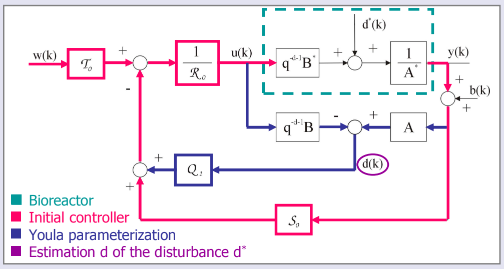
$K_E = \frac{k_{EG} G_{in} T_s}{V}$; $k_{EG} = \frac{k_5}{k_6}$ for respiratory regime; $k_{EG} = k_4$ for respiro-fermentative regime.

Associated uncertainties

- ✓ K_E variations according to the operating regime.
- ✓ neglected glucose dynamics.
- ✓ γ-variations due to μ- variations.

CONTROL STRATEGY

RST controller with Youla parametrization



Closed loop transfer functions :

$$y = \frac{B^* \mathcal{T}_o}{A^* \mathcal{R}_o + q^{-d^*} B^* \mathcal{S}_o}\cdot w + \frac{\mathcal{R}_o - q^{-1-d} B^* Q_1}{A^* \mathcal{R}_o + q^{-d^*} B^* \mathcal{S}_o}\cdot d^*$$

- ✓ The tracking behaviour is tuned with the polynomials $\mathcal{R}_o$, $\mathcal{S}_o$, $\mathcal{T}_o$.
- ✓ The rejection behaviour is tuned with the transfer function Q_1.

Q_1 design and adaptation

$$Q_1 = Q_{11} + \left(1-\gamma\, q^{-1}\right) Q_{12}$$

Internal Model Principle

d^* is rejected asymptotically if $(1-\gamma q^{-1})$ is included in $(\mathcal{R}_o - q^{-1-d} B^* Q_1)$, i.e., Q_{11} is solution of a Diophantine equation :

$$\mathcal{R}_o - q^{-1-d} B^* Q_{11} = M\left(1-\gamma\, q^{-1}\right)$$

Rodriguez and Dumur, 2003

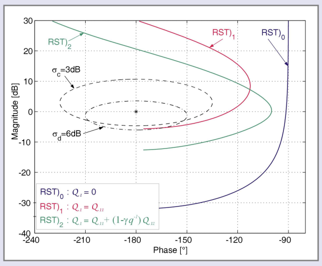
Q_{12} is selected in order to improve the robustness against modeling uncertainties and measurement noise.
It is solution of a convex optimisation problem.

On-line adaptation of Q_{11}

Due to μ-variations, Q_{11} is adapted with RLS algorithm in order to minimize the disturbance effect e_d on the output :

$$e_d = \left(\frac{M - q^{-1-d} B Q_{12}}{M}\right)\cdot\left(\frac{\mathcal{R}_o}{A_0 A_c} - Q_{11}\frac{q^{-1-d} B}{A_0 A_c}\right)\cdot d \qquad e_d^{'} \longrightarrow 0$$

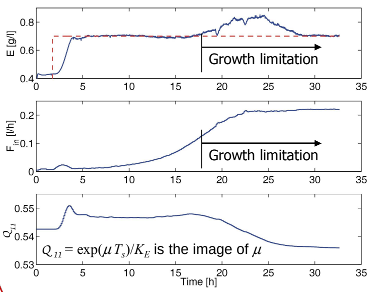
Black diagram



- ✓ The introduction of the unstable pole γ $(RST)_1$ deteriorates the robustness at high frequencies.
- ✓ Robustification with Q_{12} $(RST)_2$ is needed and provides good robustness for all frequencies, as well as better gain and phase margins.

EXPERIMENTAL RESULTS AND CONCLUSION

Experimental results



- ✓ For the first 18h, the control algorithm is able to regulate E to the setpoint. The exponential cells growth results in a exponential evolution for F_{in}.
- ✓ After 18h, the specific growth rate μ decreases (substrate limitation). The adaptation dynamics being slower than the controller dynamics, a small drift is observed on E when μ is overestimated.
- ✓ The controller is able to deal with substrate limitation.

Conclusion

- ✓ For control purpose, yeast fed-batch cultures can be modeled by a *simple linear model* describing the main macroscopic phenomenon.
- ✓ The suggested modeling methodology allows *several uncertainties* to be associated with the simplified linear model.
- ✓ An RST controller with Youla parametrization ensures the *asymptotic rejection of unstable disturbance*, a *good robustness* against modeling uncertainties and a *noise attenuation* in the control signal.
- ✓ The control algorithm includes a *disturbance model adaptation* to deal with variations of the specific growth rate.
- ✓ The suggested controller requires *very little knowledge about process* (only one yield coefficient and the on-line E-measurement).