Simple Drum-Boiler Models

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1988

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):

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Simple Drum-Boiler Models

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October 1988
**Abstract**

This paper describes a simple nonlinear models for a drum-boiler. The models are derived from first principles. They can be characterized by a few physical parameters that are easily obtained from construction data. The models also require steam tables for a limited operating range, which can be approximated by polynomials. The models have been validated against experimental data. A complete simulation program is provided.
Simple Drum-Boiler Models

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The input power from the fuel is denoted by $P$. The total steam volume is given by

$$V_t = V_{drum} - V_w + \alpha_w V_r$$

(2)

where $V_{drum}$ is the drum volume, $V_w$ the volume of water in the drum, $V_r$ the riser volume and $\alpha_w$ the average steam-water volume ratio. The total water volume is

$$V_w = V_o + V_{dw} + (1 - \alpha_w) V_r$$

(3)

The right hand side of equation (1) represents the energy flow to the system from fuel and feedwater and the energy flow from the system via the steam. Since all parts are in thermal equilibrium, the state of the system can be represented by one variable which we choose as the steam pressure. Using steam tables the variables $\rho_T$, $\rho_w$, $h_s$ and $h_w$ can be expressed as functions of steam pressure. Similarly $T$ can be expressed as a function of pressure by assuming that $T$ is equal to the saturation temperature of steam which corresponds to $p$.

This model represents the dynamics due to input power well. When the feedwater flow or the steam flow is changed it is, however, necessary to also take into account that the water and steam masses are also changing. This can be accounted for with a global mass balance.

$$\frac{d}{dt} [\rho_T V_t + \rho_w V_w] = q_s - q_w$$

(4)

The dynamics which describe how the drum pressure is influenced by input power, feedwater flow and steam flow is well captured by equations (1) and (4).

The derivative of the total water volume ($dV_w/dt$) can be eliminated between equations (1) and (4). Multiplication of (4) by $h_w$ and subtracting from (1) gives

$$\frac{d}{dt} (\rho_T V_t) + \left[ \rho_T V_t \frac{dh_s}{dt} + \rho_w V_w \frac{dh_w}{dt} + \frac{mc_p}{dt} DT \right]$$

$$= P - q_w (h_w - h_{sw}) - q_s h_c$$

(5)

The condensation enthalpy $h_c = h_s - h_w$ has also been introduced. If the boiler is provided with a good level control system the total water volume ($V_{sw}$) and the total steam volume ($V_s$) do not change much. Equation (5) can then be simplified to

$$e_{11} \frac{dp}{dt} = P - q_w (h_w - h_{sw}) - q_s h_c$$

(6)

where

$$e_{11} = h_s V_s \frac{d\rho_s}{dp} + \rho_T V_t \frac{dh_s}{dp} + \rho_w V_w \frac{dh_w}{dp} + mc_p \frac{dT}{dp}$$

Apart from steam table data it is thus sufficient to know total steam and water volumes and total metal mass. The model (6) is identical to the model in Aström and Eklund (1972). Notice however that in this case the parameters are obtained from construction data. Also notice that the term

$$q_s = \frac{1}{h_c} \left[ \rho_T V_t \frac{dh_s}{dt} + \rho_w V_w \frac{dh_w}{dt} + mc_p \frac{dT}{dt} \right]$$
can be interpreted as the total condensation flow. It is observed that the terms $dh_p/dp$ and $dh_w/dp$ are key quantities in predicting the energy and mass transfer between steam and water. These terms also appeared in the drum-boiler model of Morton and Price (1977).

3. Shrink and Swell

For some control tasks e.g. drum level control it is necessary to model the dynamics of the drum level. This is more difficult because of the shrink and swell effect. To describe this it is necessary to account for the distribution of steam and water and the transfer of mass and energy between steam and water.

The steam-water distribution varies along the risers. Partial differential equations are needed to describe this property. To keep a finite dimensional model we will assume that the shape of the distribution is known. The assumed shape is based on solving the partial differential equations in the steady state. This gives a linear distribution of the steam-water mass ratio along the risers. We will therefore assume that the ratio varies

$$\varepsilon(x) = a(x) \quad 0 \leq x \leq 1$$

where $x$ is a normalized length coordinate along the risers and $a(x)$ is the steam-water mass ratio at the riser outlet. The transfer of mass and energy between steam and water by condensation and evaporation is a key element in the modelling. When modelling steam and water separately the transfer must be accounted for explicitly. This can be avoided by writing joint balance equations for water and steam. The global mass balance for the riser section is

$$\frac{d}{d\tau} (\rho_w a V_s) + \frac{d}{d\tau} (\rho_w (1 - a) V_s) = q_{de} - q_r$$

where $q_r$ is the total mass flow out of the risers. The global energy balance for the riser section is

$$\frac{d}{d\tau} (\rho_w h_w a V_s) + \frac{d}{d\tau} (\rho_w h_w (1 - a) V_s) =$$

$$P + \rho_h a h_w - \rho_h a h_s - \rho_w h_w =$$

$$P + \rho_h a h_w - \rho_h a h_s - \rho_w h_w$$

The flow out of the risers ($q_r$) can be eliminated by multiplying equation (8) by $-h_w + \varepsilon h_s$ and adding to equation (9). Hence

$$\frac{d}{d\tau} (\rho_w h_w a V_s) - (h_w + \varepsilon h_s h_w) \frac{d}{d\tau} (\rho_w a V_s)$$

$$+ \frac{d}{d\tau} (\rho_w h_w (1 - a) V_s) - (h_w + \varepsilon h_s)$$

$$\frac{d}{d\tau} (\rho_w (1 - a) V_s) = P - \varepsilon h_s q_{de}$$

This can be simplified to

$$h_s (1 - \varepsilon) \frac{d}{d\tau} (\rho_w a V_s) + h_w (1 - a) V_s \frac{d}{d\tau} h_w$$

$$- \varepsilon h_s \frac{d}{d\tau} (\rho_w (1 - a) V_s) + \varepsilon a V_s \frac{d}{d\tau} h_w = P - \varepsilon h_s q_{de}$$

Drum Level

To calculate the drum level it is necessary to know the average steam-water volume ratio in the risers ($a_m$). We have

$$a_m = \int_a^1 a(x) d\xi = \frac{1}{a} \int_0^a (\rho_w - \rho_w a) d\xi$$

$$= \frac{1}{a} \int_0^a (\rho_w - \rho_w a) d\xi$$

$$= \frac{Q_w}{\varepsilon_a - \varepsilon} [1 - \frac{\rho_w}{\rho_w - \varepsilon} \ln \left(1 + \frac{\varepsilon_a - \varepsilon}{\varepsilon_a} \right)]$$

We can now obtain the following equation for the drum level

$$\ell = \frac{V_a + \rho_w a V_r}{A}$$

where $A$ is the wet surface of the drum. This equation tells that the drum level is composed of two terms, the total amount of water in the drum, and the displacement due to changes of the steam-water ratio in the risers. The model has the same basic form as the water-level model in Bell and Aström (1979). This model was, however, developed heuristically and not from first principles.

4. Simulations

The equations derived in Section 3 will now be summarized. The state equations are given by (1), (4) and (8). The state variables are chosen as drum pressure $p$, water volume in drum $V_w$ and average steam quality at riser outlet $x_r$. Equation (1), (4) and (8) can then be written as

$$\frac{dp}{dt} + c_{11} \frac{dV_w}{dt} + c_{12} \frac{dx_r}{dt} = P + q_w h_w - q_h,$$

$$\frac{dV_w}{dt} + c_{21} \frac{dV_r}{dt} = q_r$$

$$\frac{dx_r}{dt} = c_{32} \frac{dx_r}{dt}$$

$$c_{11} = (\frac{dV_r}{dp} + \varepsilon_a h_s + \varepsilon_a h_w) V_w + (\frac{dV_r}{dp} h_w + \varepsilon_a h_w) \frac{dV_r}{dp} +$$

$$mc \frac{dT}{dp}$$

$$c_{12} = \frac{dV_r}{dp}$$

$$c_{21} = \frac{dV_r}{dp}$$

$$c_{22} = (\varepsilon_a h_w - \varepsilon_a h_s) V_r \frac{da}{dx_r}$$

$$c_{32} = (\varepsilon_a h_w - \varepsilon_a h_s) V_r \frac{da}{dx_r}$$

$$c_{31} = (\varepsilon_a h_w - \varepsilon_a h_s) \frac{da}{dx_r}$$

$$c_{32} = (\varepsilon_a h_w - \varepsilon_a h_s) \frac{da}{dx_r}$$

$$c_{33} = (\varepsilon_a h_w - \varepsilon_a h_s) \frac{da}{dx_r}$$

$$c_{33} = (\varepsilon_a h_w - \varepsilon_a h_s) \frac{da}{dx_r}$$

$$c_{33} = (\varepsilon_a h_w - \varepsilon_a h_s) \frac{da}{dx_r}$$

Assume that the steam-water mass ratio is linear along the riser as expressed by equation (7). The average steam-water volume ratio in the risers is
To execute the simulation equation (15) has to be solved for the derivatives of the state variables. The right hand side of (15) contain input variables \( P \), \( q_w \) and \( q_s \), and functions of the state variables. Notice that downcomer flow \( q_d \) is given by equation (13). A detailed description of the simulation is given in the code in the Appendix.

Parameters
The model is characterized by the variables:
- \( V_{\text{drum}} \): drum volume
- \( V_r \): riser volume
- \( V_{\text{dc}} \): downcomer volume
- \( m \): total metal mass
- \( c_p \): specific heat of metal
- \( k \): friction coefficient

and the functions \( g_p(p) \), \( g_w(p) \), \( h_s(p) \), \( h_w(p) \), \( T(p) \), \( h_fw(p) \) which are obtained from steam tables. Quadratic approximations to the steam tables are given in the program listing in the Appendix.

Equilibrium Conditions
Equilibrium conditions are obtained from (15). Hence:

\[
q_w = g_w \\
q_s = g_s \\
P = g_p(h_s - h_{fw})
\]

The equilibrium value of the drum pressure can be determined from equation (18) since \( h_s \) and \( h_{fw} \) depend on the pressure.

Dynamic Response
Responses to steps in fuel flow and steam flow are given in Figures 1 and Figure 2. The simulations illustrate the dynamic features that are captured by the model. Figure 1 shows the response to a step change in fuel flow. The pressure responds like a pure integrator. The total amount of water in the drum increases because steam is generated in the risers. The total amount of steam in the risers increases because of the increased steam generation. The steam quality in volume ratio increases initially but it will later decrease because of the compression effect.

The drum level increases rapidly at first but the rate of increase decreases. The downcomer flow matches the steam fraction volume ratio. There is an instantaneous increase of the riser flow at the beginning of the step. The riser flow will then decrease at the same rate as the downcomer flow. Figure 2 shows the response to a step change in steam flow. The global effect is that the pressure and the volume will respond like integrators. There will, however, be a swell effect because of the initial evaporation of steam.

5. Conclusions
This paper has presented simple models for a drum boiler system. The models capture the major dynamical behaviour. They are derived from first principles and require only a few physical parameters that are easily obtained from construction data and steam tables. The behaviour has been shown by simulating step responses to fuel and steam flow changes. Reasonable results are obtained even for the difficult problems of predicting circulation flow and drum water level shrink and swell. The model can easily be augmented by equations for turbine and electrical output given in Åström and Eklund (1972, 1975) or Bell and Åström (1979) to produce a simple model for a complete boiler turbine alternator system. A strong feature is that the model capture the essence of the steam generation in a heated pipe. It has also been used successfully to model steam generation in a nuclear plant. It can also be adapted to model once-through boilers.

![Drum pressure](image1)

![Water volume](image2)

![Steam fraction mass](image3)

Figure 1. Responses to a step in fuel flow.
6. References


Appendix

CONTINUOUS SYSTEM DRUM

"Nonlinear third order model for drum-downcomer-riser"

"author K J Åström 870805"

INPUT pov qeq tsv qe
OUTPUT dL dV
STATE p Vw xx
DER dp dVx dxr
"Properties of steam and water in saturated state"

**hs** = \(a_01 + (a_{11} + a_{21} \times (p-10)) 	imes (p-10)\)

\[ a_{01} = 2.7266 
 a_{11} = -1.79284 
 a_{21} = 92.4 \]

**dsdp** = \(a_{12} + (a_{22} \times (p-10)) \times (p-10)\)

\[ a_{12} = 5.43 
 a_{12} = 7.136 
 a_{22} = 0.224 \]

**hv** = \(a_03 + (a_{13} + a_{23} \times (p-10)) \times (p-10)\)

\[ a_{03} = 1.40566 
 a_{13} = 4.26524 
 a_{23} = -1.010 \]

**rv** = \(a_04 + (a_{14} + a_{24} \times (p-10)) \times (p-10)\)

\[ a_{04} = 691.36 
 a_{14} = -1.867 
 a_{24} = 0.081 \]

**ts** = \(a_05 + (a_{15} + a_{25} \times (p-10)) \times (p-10)\)

\[ a_{05} = 311.0 
 a_{15} = 7.622 
 a_{25} = -0.32 \]

"Properties of water in subcritical state"

**hd** = \(hv + (a_{06} + a_{16} \times (p-10)) \times (p-10)\)

\[ dhdp = a_{16} + a_{26} \times (p-10) \]

\[ a_{06} = 5900 
 a_{16} = 260 \]

**rd** = \(rv + (a_{07} + a_{17} \times (p-10)) \times (p-10)\)

\[ drdp = a_{17} + a_{27} \times (p-10) \]

\[ a_{07} = 2.4 
 a_{17} = 0.72 \]

**kfw** = \(hv + (a_{08} + a_{18} \times (p-10)) \times (p-10)\)

\[ hc = hs - hv 
 hr = x \times hs - (1-x) \times hv \]

"Drum level"

\[ hV = hs - hV \]

\[ hs = V_r \times h_d \]

\[ h_d = h_d \times V_r \]

"Average steam quality volume ratio"

\[ s_2 = \frac{\text{rs}}{(\text{rs} - \text{rv})} \]

\[ a_3 = 1 + x_r (\text{rs} - \text{rv}) \]

\[ \text{dmd} = \frac{\text{rs} + a_3 \times (\text{rv} - \text{rs})}{\text{rs} - \text{rv}} \]
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INTRODUCTION

Motivation
Simple physics based models for system studies

Experimental verification
Industrial collaboration with Sydkraft AB Malmö Sweden

Progress
Slow painstaking
Eklund 1968
Åström Eklund 1972, 1975
Bell and Åström 1979
Bell and Åström 1987
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Global Energy Balance

\[
\frac{d}{dt} [\rho_s h_s V_{st} + \rho_w h_w V_{wt} + mc_p T] = P + q_{fw} h_{fw} - q_s h_s
\]  \(1\)

Total Steam Volume

\[
V_{st} = V_{drum} - V_w + a_m V_r
\]  \(2\)

Total Water Volume

\[
V_{wt} = V_w + V_{dc} + (1 - a_m) V_r
\]  \(3\)

Global Mass Balance

\[
\frac{d}{dt} [\rho_s V_{st} + \rho_w V_{wt}] = q_{fw} - q_s
\]  \(4\)

Eliminate \(dV_{wt}/dt\) between \((1)\) and \((4)\)

\[
h_c \frac{d}{dt} (\rho_s V_{st}) + \left[ \rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wt} \frac{dh_w}{dt} + mc_p \frac{dT}{dt} \right] = P - q_{fw} (h_w - h_{fw}) - q_s h_c
\]  \(5\)
\[ h_c \frac{d}{dt} (\rho_s V_{st}) + \left[ \rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wt} \frac{dh_w}{dt} + mc_p \frac{dT}{dt} \right] = P - q_{fw} (h_w - h_{fw}) - q_s h_c \]  

Rewritten as

\[ e_{11} \frac{dp}{dt} = P - q_{fw} (h_w - h_{fw}) - q_s h_c \]  

\[ e_{11} = h_c V_{st} \frac{d\rho_s}{dp} + \rho_s V_{st} \frac{dh_s}{dp} + \rho_w V_{wt} \frac{dh_w}{dp} + mc_p \frac{dT_s}{dp} \]  

Total condensation flow

\[ q_c = \frac{1}{h_c} \left[ \rho_s V_{st} \frac{dh_s}{dt} + \rho_w V_{wt} \frac{dh_w}{dt} + mc_p \frac{dT_s}{dt} \right] \]
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THE VOID MODEL

A distributed parameter system

Assuming a void distribution gives a lumped parameter model

The PDEs gives a steady state solution with a linear steam water mass ratio

Use static relation also for dynamics

Model explored for nuclear reactor models where elaborate simulation models are available
Mass Balance for Riser Section

\[ \frac{d}{dt} (\rho_s a_m V_r) + \frac{d}{dt} (\rho_w (1 - a_m) V_r) = q_{dc} - q_r \]  \hspace{1cm} (8)

Energy Balance

\[ \frac{d}{dt} (\rho_s h_s a_m V_r) + \frac{d}{dt} (\rho_w h_w (1 - a_m) V_r) = P + q_{dc} h_w - x_r q_r h_s - (1 - x_r) q_r h_w \]

\[ = P + q_{dc} h_w - x_r q_r h_c - q_r h_w \]  \hspace{1cm} (9)

Eliminate \( q_r \) between (8) and (9)

\[ \frac{d}{dt} (\rho_s h_s a_m V_r) - (h_w + x_r h_c) \frac{d}{dt} (\rho_s a_m V_r) + \frac{d}{dt} (\rho_w h_w (1 - a_m) V_r) - (h_w + x_r h_c) \frac{d}{dt} (\rho_w (1 - a_m) V_r) = P - x_r h_c q_{dc} \]

Simplify to

\[ h_c (1 - x_r) \frac{d}{dt} (\rho_s a_m V_r) + \rho_w (1 - a_m) V_r \frac{dh_w}{dt} - x h_c \frac{d}{dt} (\rho_w (1 - a_m) V_r) + \rho_s a_m V_r \frac{dh_s}{dt} = P - x_r h_c q_{dc} \]  \hspace{1cm} (10)
Drum Level

Average steam-water volume ratio

\[ x = \frac{\rho_s a}{\rho_s a + \rho_w (1 - x)} \]

Solving with respect to \( a \)

\[ a = a(x) = \frac{\rho_w x}{\rho_s + (\rho_w - \rho_s) x} \]

Assume

\[ x(\xi) = x_r \xi \quad 0 \leq \xi \leq 1 \] (11)

Hence

\[ a_m = \int_0^1 a(x_r \xi) d\xi = \frac{1}{x_r} \int_0^1 a(x_r \xi) d(x_r \xi) \]

\[ = \frac{1}{x_r} \int_0^{x_r} a(x) dx \]

\[ = \frac{\rho_w}{\rho_w - \rho_s} \left[ 1 - \frac{\rho_s}{(\rho_w - \rho_s) x_r} \ln \left( 1 + \frac{\rho_w - \rho_s}{\rho_s} x_r \right) \right] \] (11)

\[ \ell = \frac{V_w + a_m V_r}{A} \] (12)
Downcomer Flow

Momentum balance

\[ a_m V_r (\rho_w - \rho_s) = \frac{1}{2} k q_{dc}^2 \]  
(13)

Riser flow from (8)

\[ q_r = q_{dc} - \frac{d}{dt} (\rho_s a_m V_r) - \frac{d}{dt} (\rho_w (1 - a_m) V_r) \]  
(14)
Summary

\[ \frac{d}{dt} \left[ \rho_s h_s V_{st} + \rho_w h_w V_{wt} + m c_p T \right] \]
\[ = P + q_{fw} h_{fw} - q_s h_s \]  
(1)

\[ \frac{d}{dt} [\rho_s V_{st} + \rho_w V_{wt}] = q_{fw} - q_s \]  
(4)

\[ h_c (1 - x_r) \frac{d}{dt} \left( \rho_s a_m V_r \right) + \rho_w (1 - a_m) V_r \frac{dh_w}{dt} \]
\[ - x h_c \frac{d}{dt} \left( \rho_w (1 - a_m) V_r \right) + \rho_s a_m V_r \frac{dh_s}{dt} \]
\[ = P - x_r h_c q_{dc} \]  
(10)

Choose \( p, V_w, \) and \( x_r \) as state variables.

Simulation Model

\[
\begin{align*}
    e_{11} \frac{dp}{dt} + e_{12} \frac{dV_w}{dt} + e_{13} \frac{dx_r}{dt} &= P + q_{fw} h_{fw} - q_s h_s \\
    e_{21} \frac{dp}{dt} + e_{22} \frac{dV_w}{dt} + e_{23} \frac{dx_r}{dt} &= q_{fw} - q_s \\
    e_{31} \frac{dp}{dt} + e_{33} \frac{dx_r}{dt} &= P - q_{dc} x_r h_c 
\end{align*}
\]  
(15)
\[ e_{11} = \left( \frac{d\rho_s}{dp} h_s + \rho_s \frac{dh_s}{dp} \right) V_{st} \]

\[ + \left( \frac{d\rho_w}{dp} h_w + \rho_w \frac{dh_w}{dp} \right) V_{wt} + m c_p \frac{dT_s}{dp} \]

\[ e_{12} = \rho_w h_w - \rho_s h_s \]

\[ e_{13} = (\rho_s h_s - \rho_w h_w) V_r \]

\[ e_{21} = \frac{d\rho_s}{dp} V_{st} + \frac{d\rho_w}{dp} V_{wt} \]

\[ e_{22} = \rho_w - \rho_s \quad (16) \]

\[ e_{23} = (\rho_s - \rho_w) V_r \frac{d a_m}{d x_r} \]

\[ e_{31} = \left[ (1 - x_r) h_c \frac{h\rho_s}{dp} + \rho_s \frac{dh_s}{dp} \right] a_m V_r \]

\[ + \left[ \rho_w \frac{dh_w}{dp} - x_r h_c \frac{d\rho_w}{dp} \right] (1 - a_m) V_r \]

\[ e_{33} = [(1 - x_r) \rho_s + x_r \rho_w] h_c V_r \frac{d a_m}{d x_r} \]
Parameters

\[ V_{drum} \]  drum volume
\[ V_r \]  riser volume
\[ V_{dc} \]  downcomer volume
\[ m \]  total metal mass
\[ c_p \]  specific heat of metal
\[ k \]  friction coefficient
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Step in Fuel Flow

Figure 1. Responses to a step in fuel flow.
Step in Steam Flow

Figure 2. Response to a step
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EXPERIMENTS

P16-G16 at Öresundsverket

Steinmuller boiler Stal-Laval turbine. Active power 160MW.

Controllers disconnected. PRBS like perturbations introduced in fuel flow, feedwater flow and steam valve at high and low load.
Fuel Flow Changes at Low Load

Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant
Turbine Valve Changes at Low Load

Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant
Feedwater Flow Changes at Low Load

Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant
Fuel Flow Changes at High Load

Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant
Turbine Valve Changes at High Load

88.02.05 - 20:41:54 nr: 1

Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant
Feedwater Flow Changes at High Load

88.02.05 - 19:45:37 nr: 1

Drum pressure. 1=model, 2=plant

Electrical output. 1=model, 2=plant

Drum water level. 1=model, 2=plant
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CONCLUSIONS

Promising results

Some details remain

Further experiments

Simplifications

Control design