Pressure and Flow Control of a Pulverized Coal Injection Vessel

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Abstract

This paper deals with model-based pressure and flow control of a fine coal injection vessel for the use of the blast furnace injection process.

By means of system modeling and identification, the structure and behavior of the coal injection vessel are analyzed. It is shown that by use of model-based design, the control goals can be reached and the control performance can be significantly improved compared to the conventional PI-controllers. Several dynamic models of the plant are developed. A number of control strategies are presented and compared by means of practical tests. The LQG design method is used to design the controllers. All the controllers are validated through experiments on the coal injection plant at SSAB Tunnplåt in Luleå, Sweden.

1. Introduction and Background

Iron is a mass product, produced in blast furnaces and later refined to steel. This could lead to the conclusion that the process is efficient and optimized, which is not completely true. It has become more usual to bring down the cost factors in the iron production by reducing the share of undesired by-products or the costs of energy supply.

Although coke is one of the most expensive energy carriers, it is common to use it in iron production. In Luleå , SSAB Tunnplåt reduces the production costs by partly substituting coke and using pulverized coal instead. Pulverized coal is about 40% cheaper than coke, which fact makes it very attractive.

Since pulverized coal, in its pure form, is highly inflammable even under normal conditions, it is difficult to supply it to the process. Therefore, it is important to keep the pulverized coal isolated from the air, which can be done by using a pneumatic conveying device. The used coal injection plant is planed, designed and constructed by BMH (Babcock Materials Handling in Hamburg, Germany), where two injection vessels are used alternatively to maintain a continuous injection.

Injecting coal powder in the blast furnace at a high rate of about $190 kg/thm$ makes the blast furnace process very sensitive. According to [1], the process outage becomes critical, due to the fact that large amounts of coal are not delivered to the furnace. The prime concern in fine coal injection is therefore a constant coal mass flow to the blast furnace.

Since the injection vessels operate under high pressure, pressure stabilization during the injection phase is also a control concern, but somewhat of lesser importance than mass flow control. In the experiments, it appears that a constant pressure in the injection vessel makes flow stabilization easier.

2. Coal injection plant

The coal injection plant is a highly automated plant, where incoming raw coal is stored, grinded, dried and finally injected into the blast furnace. During operation, human interaction is only needed for set point adjustments.

Fig. 1 shows the structure of the plant, where the different sections are marked and referred to by the capital letters in the marked area. The sections A, B, C are common for the two fine coal silos. Sections D, E and F, G belong to Blast Furnace 1 and Blast Furnace 2, respectively. This article deals only with the coal injection of Blast Furnace 2. Therefore, the emphasize is placed on section E.

A closer description of each section and its functionality can be found in [2].

2.1. Injection process

Principally, the injection process can be divided into two separate phases : a high-pressure and a low-pressure phase, where, as the names already imply, the pressure in the injection vessel is high or low, respectively.

One vessel is depressurized, charged and pressurized while the other vessel is injecting coal powder. To facilitate process identification and control, the high pressure and low pressure phases are sub-divided into more specific phases.

Fig. 2 shows one process cycle of injection vessel S21. A represents the low pressure phase and B to E belong to the high pressure phase. In Table 1, the nomenclature used in the sequel to refer to process phases is summarize.

In [2], the process phases are described more in detail. This paper deals only with the injection phase. Some particular specifications, from which the primary control goals can be derived, are:

• The pressure in the injection vessel is constant.

• The coal mass flow to the blast furnace is constant

Phase	Name	Description
A	Charging	The pressureless vessel is filled with coal powder
B	Pressurizing	The injection vessel is set under pressure
C	Pressure holding	Standby until the other vessel has finished injection
D	Injection	The coal powder is injected into the blast furnace
E	Ventilation	Depressurizing and ventilation of the vessel

Table 1: Process phases

- The mass of the injection vessel follows a ramp, where the slope of the ramp depends on the coal mass flow set-point.

- The injection phase ends when a minimum weight is reached.

3. Existing control unit

The control unit of the fine coal injection plant consists of two independent loops. One loop is for injection vessel pressure stabilization, and the other is for controlling the coal mass flow to the blast furnace. The process working cycle duration depends on the actual coal mass flow set point.

The pressure control loop is implemented by means of a PI controller, to achieve a zero steady state control error. The controller performance is exhibited in Fig. 3a. The coal mass flow controller is also a PI controller. However, since the coal mass flow is not directly measured in this particular installation, the coal mass flow is evaluated from the vessel's weighing system readings. The computations involve a differentiation, which naturally results in amplification of the measurement noise. Thus, low-pass filtering is applied and a set point compensation is employed to correct measurement errors.

As seen in Fig. 3b, the mass flow controller fails to drive the control error to zero during the injection phase. The shortcomings of the existing control strategy become even more prominent when the deviation of the mass loss in the injection vessel from the ideal mass loss is analyzed (Fig. 3c).

To recapitulate, under the existing control laws, the pressure p in the injection vessel is oscillative and the coal mass flow is not held constant. In the sequel, alternative ways of controlling the injection vessels are discussed.

4. Modeling

Basically, an injection vessel is a pressurized tank process (Fig. 4).

There, two output signals are available:

- Pressure p in the vessel

- Coal mass m_C, which is the integral of the coal mass flow to the blast furnace. The coal mass flow is not measurable, as no flow meter is installed.

Natural control signals are:

- Valve opening u_N of the pressure control valve (PCV)

- Valve opening u_C of the flow control valve (FCV)

Since not all signals are suitable for process control, some assumptions are made, for the sake of model simplification:

1. Variations of the pressure in the nitrogen net are small and p_N is assumed to be constant.

2. The pressure p_T at the injection point in the transportation pipe is constant.

3. Temperature variations are small.

4. No nitrogen leakage from the injection vessel during the injection phase ($u_I = u_V = 0$, and these valves are tight)

5. The flow due to the weight of the coal is negligible.

A non-linear behavior of the injection vessel has been observed in [3], and a dynamic model based on the physical contiguities has been suggested.

In an earlier study [4], a black-box model of the injection vessel has been developed and successfully used for a pressure controller design. Following the recommendation worked out in the study, SSAB Tunnplåt in Luleå carried out constructive changes in the coal injection plant hardware. These changes in the equipment crave model validation to be performed anew.

According to the assumptions made, two input signals can be manipulated and two output signals measured, the opening of the valves u_N and u_C, the pressure p and the mass m. These signals are used to identify and to control the process.

4.1. Identification

When it comes to coal powder flow control, two additional models are needed to describe the process dynamic properties. One model whose output is the coal mass m_C and the input is the opening of the FCV u_C. The second model is a multiple input, multiple output (MIMO) model with p, m_C as outputs and u_N, u_C as inputs. The latter can be used to design a MIMO controller for the process. In order to spare place, no numerical values are given. These values can be reviewed in [2].

Identification and validation data sets are logged on the process with a sampling time of $1s$. Exerting the least-squares method, a SISO model for the mass and a MIMO model for the mass and pressure are identified. The resulting models are presented in the ARX-form. Equation 1 gives the SISO model.

$$m(t) = \frac{b_{m1}q^{-1}}{1 - a_{m1}q^{-1}} \cdot u_C(t) \qquad (1)$$

The MIMO model is defined by the polynomial matrices

$$\mathbf{A}(q^{-1}) \begin{bmatrix} p(t) \\ m(t) \end{bmatrix} = \mathbf{B}(q^{-1}) \begin{bmatrix} u_N(t) \\ u_C(t) \end{bmatrix} \qquad (2)$$

with

$$\mathbf{A}(q^{-1}) = \mathbf{I} + \mathbf{A}_1 q^{-1} + \mathbf{A}_2 q^{-2} \qquad (3)$$
$$\mathbf{B}(q^{-1}) = \mathbf{B}_1 q^{-1} + \mathbf{B}_2 q^{-2} \qquad (4)$$

where $\mathbf{A}_1, \mathbf{A}_2, \mathbf{B}_1, \mathbf{B}_2$ are 2×2 matrices containing the polynom coefficients and $\mathbf{I}$ is the identity matrix.

Following the suggestions of [5, chapter 11], two validation tests are applied:

1. Common sense test

2. Statistical test

To spare place only the common sense validation plots are presented. Figure 7a,b shows the validation plot for the two SISO models and Fig. 7c,d for the MIMO model.

For controller design, the acquired matrix transfer functions are converted into state space models. Furthermore, the model order of the MIMO model has been reduced. The resulting state space equations for the SISO and MIMO models are presented below.

$$m(k + 1) = \Phi_m m(k) + \Gamma_m u_C(k) \qquad (5)$$

$$\begin{bmatrix} p(k+1) \\ m(k+1) \end{bmatrix} = \Phi \begin{bmatrix} p(k) \\ m(k) \end{bmatrix} + \Gamma \begin{bmatrix} u_N(k) \\ u_C(k) \end{bmatrix} \qquad (6)$$

where Φ_m, Φ are the system matrices and Γ_m, Γ are the input matrices of the state space model (Φ_m, Γ_m are scalar values and Φ, Γ are 2×2 matrices).

In both cases the state vectors are transformed so that the states coincide with the outputs and, therefore, have a physical meaning.

5. Control strategies

As mentioned before, the control objectives are to maintain a constant pressure in the injection vessel and to guarantee a constant coal mass flow from the injection vessel to the blast furnace. Though, a steady coal mass flow has a higher priority than pressure stabilization. This can be achieved by pursuing different strategies. Here are two of them:

1. Two separate control loops for the pressure and the mass.
   One unit controls the vessel pressure and the other controls the coal powder mass, where the mass has to follow a pre-defined ramp. The slope of the ramp is the coal mass flow set point. For the controllers design, two SISO models for the plant are used.

2. A MIMO design controlling the pressure and mass.

Strategy 1 and 2 both have their own advantages and disadvantages.

Strategy 1 is based on SISO models which makes the controller design and implementation easy to handle. The main disadvantage is that the couplings in the process are not taken in account. To achieve a better control performance, the effects of the coupling between the injection vessel pressure and the fine coal flow have to be modeled as disturbances.

Strategy 2 takes the couplings into consideration. Furthermore, this strategy has one more degree of freedom, as the two actuators are used together to achieve the control objectives. Another advantage is that the controller can eventually be tuned so that the two loops work separately. In this case, a controller similar to that of Strategy 1 is obtained, and yet the couplings in the plant are accounted for through the model. A relative disadvantage is that the design process appears to be more complicated.

An optimal design method is used to design the controllers. The separate loops and the MIMO design are based on the so-called linear quadratic gaussian (LQG) theory, as described in [6]. It is also a major design tool for multivariable linear systems.

Normally, assuming state feedback, a proportional-integral control law is chosen to eliminate the steady state error. However, controlling the fine coal mass, one of the closed-loop system outputs has to follow a ramp. Then, the use of a single integrator leads to a constant steady state response error. Thus, a double integration is used to drive the error in reference signal following to zero. In order to recast this control law into the framework of LQG design, the process models have to be augmented with a double integrator.

For the resulting system, a steady state Kalman filter is designed, in order to obtain filtered versions of the measured signals. The steady state Kalman filter seems to be sufficiently fast, as the process itself is very slow.

Furthermore, to reduce the controller settling time and retain a smoother set point change response, a feedforward signal from the desired coal mass flow to the valves is introduced. The design ideology presented in [7, chapter 6] is adopted. The feedforward signal can be introduced both in the MIMO controller and the separate pressure and flow control loops.

Fig. 5 depicts two separate control loops with additional feedforward path and Fig. 6 shows a similar solution for the MIMO design.

6. Practical tests

In this section, two different tests are described. Firstly, the MIMO controller is tested and, secondly, a pressure control is run, with the existing controller for the mass flow. The latter test is important, as it demonstrates that a better pressure control leads to less variations in the mass flow, although the controller for the mass flow has not been changed. Furthermore, the couplings in the

	old PI	new PI	Combined	MIMO
mass $[kg]$	51.8	11.3	6.8	1.5
pressure $[kPa]$	5.1	5.1	1.0	1.0
mass flow $\left[\frac{t}{h}\right]$	1.8	1.6	0.9	1.0

Table 2: Standard deviations

	Improvement
mass	79%
pressure	86%
mass flow	35%

Table 3: Control performance improvements

plant dynamics can be illustrated by this test too, since there would be no change in the control of the mass flow otherwise.

In the following four controllers are compared to each other :

1. Existing controller (PI). This controller is referred to as *old PI controller*.

2. Existing controller (PI, better tuned). In the course of project, the tuning of the PI controller has been improved. Naturally, this one is denoted as *new PI controller* in the comparative study.

3. Combined controller (LQG-design). The model-based controller from the preliminary study [4] is used to control the vessel pressure and the existing controller for the mass flow is used. All curves of this control solution are entitled *combined controller*.

4. MIMO controller (LQG-design). As this controller is completely model-based the curves are entitled *model-based controller*.

Fig. 8 depicts performance for each controller. As expected, the MIMO controller yields the best result. This can also be seen by comparing the pressure deviation, (Fig. 9).

From the experiments on the plant, it becomes clear that in the process there exist strong dynamic couplings that can not be neglected in the controller design. Although the mass flow control has not been changed, the overall controller performance becomes better because of a tighter pressure control loop.

Table 2 shows the standard deviations achieved by the corresponding controllers. Once again, it can be seen that the MIMO controller produces the best results.

Performance improvements achieved by the MIMO controller compared to the new PI controller are given in Table 3.

7. Conclusions

Identification and control of the coal injection process are discussed. It is shown that by use of model-based designs, the flow and pressure control of the coal injection

vessel could be significantly improved. With the new control, the coal mass flow can be used as a control parameter for the blast furnace. High injection rates can be used and more coke substituted.

8. Acknowledgment

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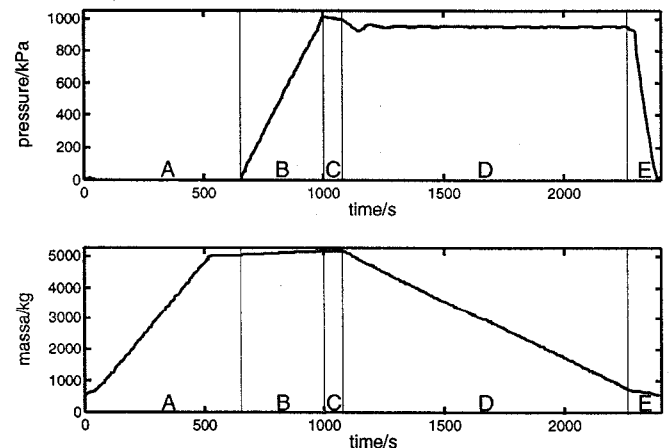[7] R. Stengel, *Stochastic Optimal Control*. John Wiley & Sons, Inc., 1986.

Fig. 2: Process working cycle of injection vessel S21

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COAL INJECTION PLANT

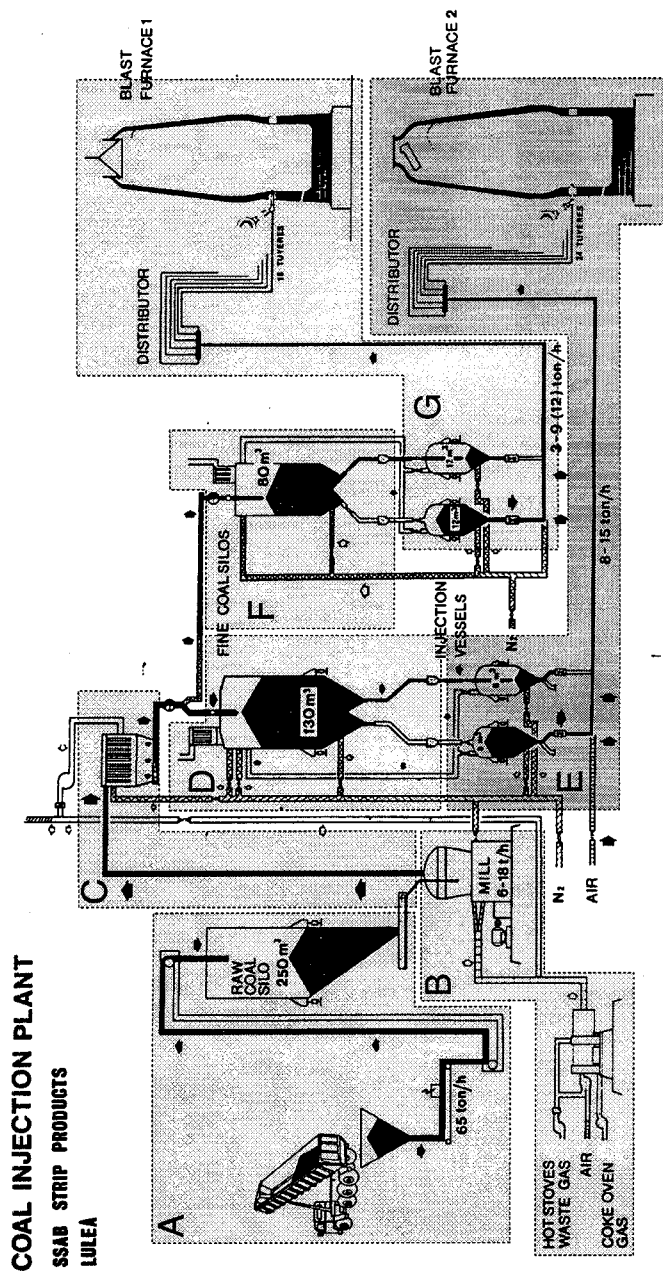SSAB STRIP PRODUCTS
LULEÅ

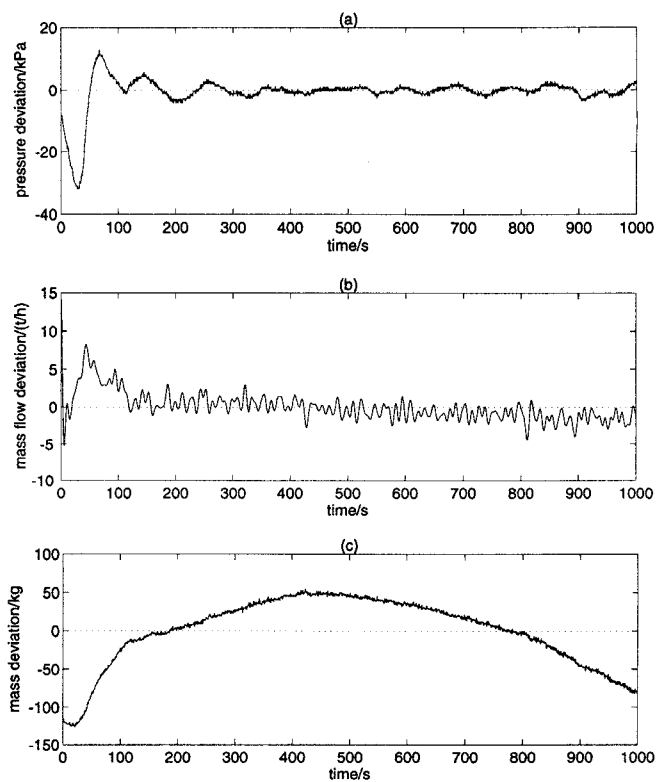Fig. 1: Coal injection plant

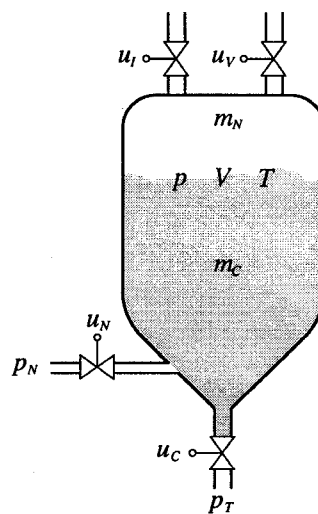Fig. 3: Performance of the existing control units

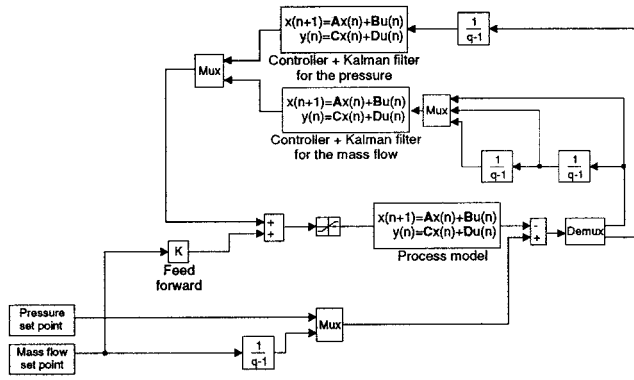Fig. 4: Schematic drawing of an injection vessel

Fig. 5: Block diagram of the two separate control loops with implemented feed forward (Simulink)
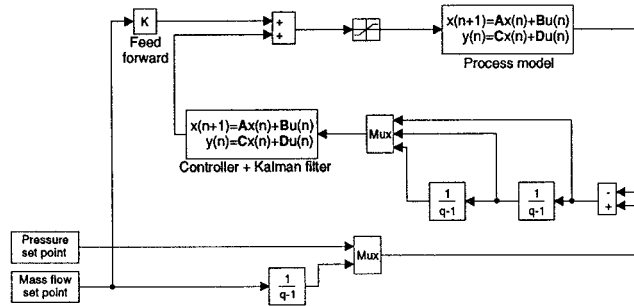

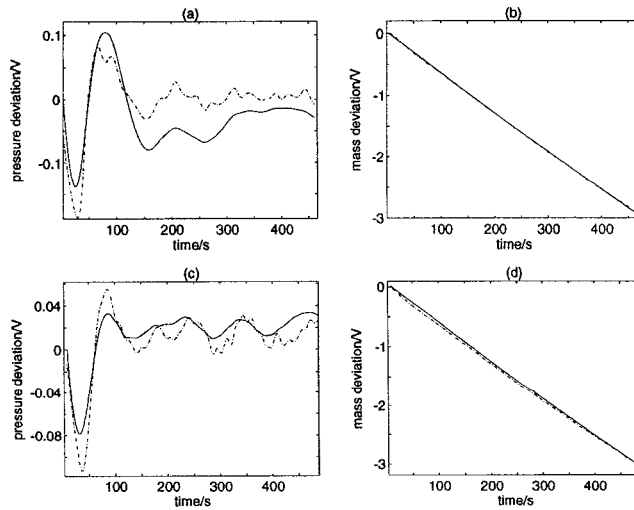Fig. 6: Block diagram of the MIMO controller with implemented feed forward (Simulink).

Fig. 7: Common sense tests. Measured output (dashed-dotted) and simulated output (solid)
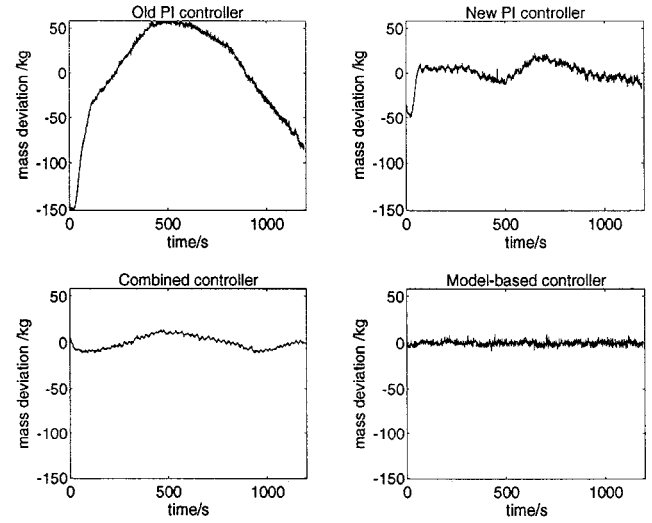

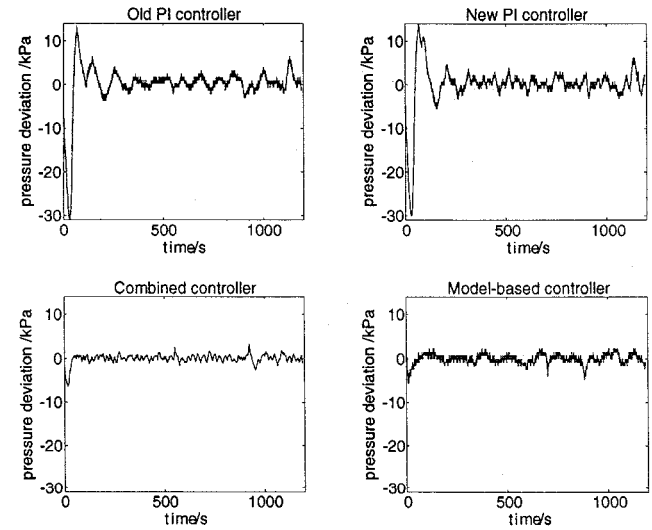Fig. 8: Comparison of the mass deviation of the four controllers

Fig. 9: Comparison of the pressure deviation of the four controllers

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