Model Predictive Control of compressor installations

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SYNOPSIS

Compressor systems are often the heart of an installation. Therefore the control of the compressor system determines to a large extent the performance of the installation as a whole. In gas transportation networks a minimum pressure at various delivery points has to be guaranteed and decisions have to be made to start up compressors in time based on predictions of the demands. In processing plants the operating conditions vary due to changes in feedstock and product specifications, which requires that the compressor system will be controlled in such a way that the processing plant is kept 'on spec' at all conditions and for a minimum power consumption.
In this paper the results of a study of the applicability of Model Predictive Control (MPC) on compressor systems is presented. MPC offers an adaptive and optimising control strategy which deals with multiple goals and constraints such as compressor surge, maximum driver power and maximum flow (stonewall point). The capabilities of MPC are demonstrated by simulation study of a typical compressor station. The results of this simulation study show that the MPC concept is a feasible option for the control of complex compressor systems and offers a flexible solution for a control problem with control objectives which vary in time.

1. INTRODUCTION

Large turbo compressors are used for boosting pressure in gas distribution networks. Also in the process industries large turbo compressors are applied for various purposes. For all applications the capacity control of a compressor station is important for the reliable delivery of the required amount of gas at the required conditions. Because the capacity of a turbo compressor is limited to a certain "operating envelope", special requirements are put on the controllers to deal with constraints.
In this paper the results are presented of an investigation of the applicability of Model Predictive Control, or shortly MPC, for compressor installations. The study is based on a typical compressor station consisting of two compressors running in parallel. The applicability of MPC is investigated by means of a non linear computer model of the compressor station.
In the next section first a short introduction is given on MPC related to compressor control. Then the test case and the computer model which simulates the compressor station are described. The results of a simulation study of the MPC control of the compressor station using the MPC tool PRIMACS are discussed. The paper is concluded with general conclusions about the applicability of MPC on compressor installations and the requirements of the MPC controller.

2. MODEL PREDICTIVE CONTROL (MPC)

Model Predictive Control (MPC) is a control strategy that uses a model of the controlled process. At discrete points in time the control action at that time and the control actions to be taken at a number of future time points are optimised. See figure 1. This is done by predicting the future response of the system using a model of the process. Based on this prediction, an objective function is optimised on-line with regard to the future control inputs to the process. The time period for which the prediction is made is called "prediction horizon" and the time period for which the control inputs are optimised is called the "control horizon".

With the definition of the objective function a combination of goals for operation of the system is quantified, for instance minimum energy consumption and maximum flowrate. The relative importance of the goals is specified by means of weighting factors. In the optimisation it is possible to take constraints into account, such as maximum power consumption, surge limit and maximum and minimum positions of control valves.

Each time step the values of the inputs for the next time step are determined such that the objective function is optimal over the prediction horizon. This optimisation is repeated at the next time step while shifting both horizons one time step ahead. This mechanism is known as moving or receding horizon. An important limitation of the process is the computation time required to do the optimisation. The optimisation has to be completed in one time step. As the calculation of the response of the model is an important part of this, the model of the process has to be as simple as possible. Therefore in general linear models are applied. As for non linear system like a compressor station this is insufficient, successive linearisation has been applied. In this technique the parameters of the model are updated every time step for the actual work point.

Unless the model of the process, in this case the compressor station, is perfect, differences between the response of the real process and the model have to be resolved. Therefore, in the implementation of MPC in the PRIMACS tool, the model is tuned to the process by measurements. In this way the control loop is closed and the scheme shown in figure 2 emerges. The tuning is done by means of a Kalman filter, which corrects the state parameters of the process model.

3. AN EXAMPLE: MPC CONTROL OF A BOOSTER STATION WITH TWO COMPRESSORS

Compressors are widely used in gas distribution networks and process installations for boosting up pressure to the required level. In general a combination is made of a number of compressors with process equipment in a compressor station. The function of the compressor station is to deliver a certain flow rate at a required pressure level. The required flow rate and pressure may vary depending on the users or processing plant. Moreover the compressor station may also have to deal with a varying inlet pressure and gas composition.

In figure 3 a typical configuration of a compressor station consisting of two turbo compres-sors in parallel (almost the simplest configuration possible) is shown. The compressors are driven by a gas turbine with variable speed. The capacity of the compressor can be controlled by the speed or by a throttle valve in the suction or discharge line. Using throttle valves for capacity control is not very popular because of the dissipation of energy this causes. For anti surge control (and start-up) a by pass around each compressor is installed. When the surge line is approached the anti surge controller will open the by pass valve shifting the operating point of the compressor away from the surge line. To achieve a small response time, the by pass line has to be short. However, when the compressor has to operate with open by pass for a longer period, the recycled gas will be heated too much. Therefore another by pass is installed around the entire station which contains a cooler.

For each compressor there are three controlled variables (inputs): the position of the throttle valve in the suction, the position of the recycle valve and the power supply.

The pipe system consists of a suction system, a discharge system and a user or group of users. The suction system consists of a reservoir with constant pressure and for each compressor a throttle valve and a suction pipe. The hot by pass line ties in downstream of the throttle valve. The discharge system consists of a discharge pipe and a hot recycle line for each compressor. Both discharge lines feed into a common header. The users are represented by a control valve downstream of the header. The user demands are represented by variations of the position of this control valve.

For each compressor there are three controlled variables (inputs): the position of the throttle valve in the suction, the position of the recycle valve and the power supply. In general the response of an MPC controller will be too slow to be used for fast phenomena like surge. To avoid surge separate fast controllers have to be installed. These anti surge controllers use the recycle valves of the compressors. The objective of the MPC controller is to avoid that the anti surge controller comes into action. The MPC controller uses the throttle valves, the recycle valves and the power supplies of the compressor. In addition the cold recycle valve is used for control.

4. MODEL ASSUMPTIONS AND SIMPLIFICATIONS

The compressor station is in this case simulated by means of a computer model. This is a detailed model in comparison with the model used in the MPC controller. Nevertheless, a number of simplifying assumptions have been made to make the study simpler, but do not affect the conclusions about the applicability of MPC. For this study of the generic compressor station (simulation of the process) the following assumptions have been made:

1. The model is built from lumped components (describing compressors and valves) and connecting volumes. The model assumes ideal gas, adiabatic flow through valves, polytropic compression with constant efficiency, homogeneous volumes and no pressure drop over volume elements
2. For the components, quasi static mass flow relationships are solved. In the connecting volumes, conservation laws for mass, momentum, and energy are solved.
3. Since the model is built up out of modules, the configuration can be adapted easily to include more compressors (connected in parallel or in series), buffer tanks, or valves.
4. In this example the dynamics of the driver, a gas turbine, is neglected. In reality, the fuel rate and the inertia of the gas turbine determines the available power

during transients. In the present model this inertia is neglected. Instead, a move rate on the power input is imposed. In this example also valve dynamics and dead times are not included.

5. The two compressors are assumed to be almost identical. Small differences are applied, representing the practical situation in which “identical” compressors appear to differ. In fact, the mass flow axis of the characteristic of compressor b is multiplied by a factor 1.1 and the efficiency of compressor a is set to 0.70, while the efficiency of compressor-b is 0.60. The applied compressor map is shown in figure 5 for reference inlet conditions
6. The suction pressure and temperature are assumed to be constant, i.e. the station does not exert upstream influences.
7. Only one user has been assumed. Multiple users can be simulated by superposition of load patterns.

5. CONTROL OBJECTIVES

General control objectives for the compressor station are an integration of surge avoidance and capacity control. Defining the mass flow through the "user valve" as the capacity, two control cases have been considered:

1. A user with a reference flow pattern. The control objective is to deliver this flow pattern as close as possible in spite of the disturbances.
2. A user with an actual flow pattern. The control objective is in this case to keep the delivery pressure within specified margins.

In both cases there are the following constraints:

- Surge constraints on the separate compressor characteristics.
- Minimum and maximum rotational speeds for separate compressors.
- Maximum temperature in the compressor outlet plenum. (Temperature build-up due to hot-recycling.)
- Minimum and maximum pressure level in the header.
- Minimum, maximum and move constraints on the power supply to the separate compressors and on the control valves positions.

6. MPC IMPLEMENTATION

Models. The models used in the MPC, as discussed in section 2, have to be as simple as possible in order to minimise the response time. Therefore linearised models are used for prediction and optimisation. The coefficients of the model are recalculated every time step to deal with the non linearity of the system. With this technique, called successive linearisation, the actual workpoint is followed.
To study the robustness of the MPC both parametric model mismatches, such as deviation of efficiency, inertia and compressor characteristic, as well as unmodelled disturbances have been introduced.

Controller tuning. For optimal performance of the MPC the prediction and control horizons, p and m, have to be selected carefully. For this case p=30 and m=8 time steps have been selected.
The weighting factors in the optimisation criterion have to be selected according to the priority of the controlled parameters. These factors reflect the relative importance of trajectory errors and control effort. The control effort is defined by input moves. Since only input moves are weighted, a (high) weighting factor avoids that the

control valves make many moves. On tbe other hand, a weighting factor of 0 allows arbitrary control moves (only limited by the constraints) and the system moves back and forth between constraints.

Load balancing. Two load balancing criteria have been evaluated: maximum and equal distance of the workpoint of each compressors to the surge line, and alternatively minimum power consumption of the station. To implement these load balancing criteria, additional model outputs are defined, which are computed out of the measured variables and are defined as follows:

First, the distance to the surge line (dSurge) is defined as:

$$dSurge = \frac{\text{actual\_ mass flow}}{\text{mass flow at surge for the same rotational speed}}$$

The variable dSurge should be less than 1 to avoid surge. (this is a constraint).
In the case of load balancing, the difference of both "distances to surge line" is used as a controlled output. A setpoint of 0 to variable dBalance guarantees an equal distance to the surge line:

$$dBalance = dSurge\_A - dSurge\_B$$

Next, the deviation from the minimum required power (dPower) is defined as:

$$dPower = \frac{actual\_power}{\min imum\_power} = \frac{Power\_A + Power\_B}{TotalmassflowC_p \left[T_{suction} \left(\frac{P_{header}}{P_{suction}} \right)^{\frac{\gamma-1}{\gamma\eta_{ideal}}} - T_{suction} \right]}$$

The second load-balancing strategy uses *dPower* to minimise power input to the compressor station. A minimal power consumption corresponds with setpoint 1.0.

7. SIMULATION RESULTS

A large number of cases have been studied. Here the results of one case are discussed. This is the case for an actual load pattern and power load balancing. The simulation results with and without a set point on the header pressure are compared. Summarising, the following options are selected for the simulations in this section:

- A reference value of 1.0 on the deviation ratio *dPower* with a set point weight of 0.1.
- A surge constraint on *dSurge* at 0.95 for both compressors.
- A minimum (1.6 bar) and maximum (2.1 bar) constraint on the pressure in the header.
- The maximum power input is 100 kW per compressor.
- The rotational speed is limited between 420 - 460 rps.
- Additional set point on the header pressure at 1.85 bar, weight 0. 1.

The results of the simulation are gathered in figure 6 and figure 7.

During the simulation, the user load varies a factor 3, e.g. between a relative flow of 0.45 and 1.35 (see figure 6a). In spite of these large disturbances, the header pressure does not exceed its constraints (figure 6). Also other constraints for surge, maximum power input and rotational speed are not exceeded.

It appears from figure 6a that the effect of the additional set point on the pressure on the delivered mass flow is rather small. As to be expected, the effect on pressure is significant. In case of a set point, the pressure always returns to its fixed set point, while a free pressure level, at least between a minimum and a maximum pressure, tends to the lower constraint value (but does never exceed this boundary).

Clearly, the fixed pressure level takes more power (figure 7). The power ratio of both simulations is approximately the same. This is caused by the definition of ideal power relative to the pressure in the header. Comparing this simulation with simulations (not shown here) where the traditional distance to the surge line is controlled instead of the power ratio, shows that the power ratio during transients is slightly better, and that the actual power consumption is indeed reduced. This demonstrates that power consumption can be minimised by the MPC controller.

In figure 8, the distance to the surge line (for compressor a only) for the above simulations. Clearly, the constraint on the distance to the surge line is hardly exceeded the safety limit of 0.95. This means that MPC is able to integrate surge avoidance with capacity control.

8. EFFECT OF MODEL MISMATCHES

The robustness of the MPC concept has been tested by running a case in which the following parameters in the simulation model have been changed:

- The suction pressure has been increased by 10%
- The efficiency of the compressors have been increased by 0.05.

The results show that, apart from the first ten samples, when the filter initialises, there is hardly any difference with the former simulation runs. This demonstrates that the filter is perfectly capable to compensate for model mismatches.

9. DISCUSSION AND CONCLUSIONS

In this simulation study it is demonstrated that with this MPC configuration it is possible to implement two extreme control cases: one in which a reference load pattern has to be followed and one in which the system has to respond on an actual load pattern. In both cases it is possible to integrate surge control and capacity control. The feasibility of a practical implementation depends on the time required to calculate the model parameters and the (optimised) response at the next time step. For an implementation of MPC on a laboratory turbine compressor installation a time step of the order of one second has been achieved using a fast Personal Computer. As for the capacity control of a compressor station time steps of the order of one minute is fast enough, the MPC concept is feasible for this kind of applications.

The application of MPC can replace multiple control loops which are used nowadays in compressor control. MPC allows optimal control of the installation including surge avoidance without ineffective override control of a dedicated surge controller. As the MPC will effectively avoid surge, the surge controller can be simplified to a safety switch. Moreover, MPC facilitates anticipation on future disturbances. This is useful when predictions can be made of the user behaviour or when a switch in operating conditions is planned in advance.

Though the example studied is simple, the capabilities of MPC for the control of compressor installations are demonstrated. Especially interaction between all control inputs and controlled outputs in combination with perfect constraint handling and dynamic optimisation is shown to benefit the performance of the station. Moreover, MPC offers opportunities for anticipation to future set point changes or disturbances and the application of relevant optimisation criteria like power minimisation.

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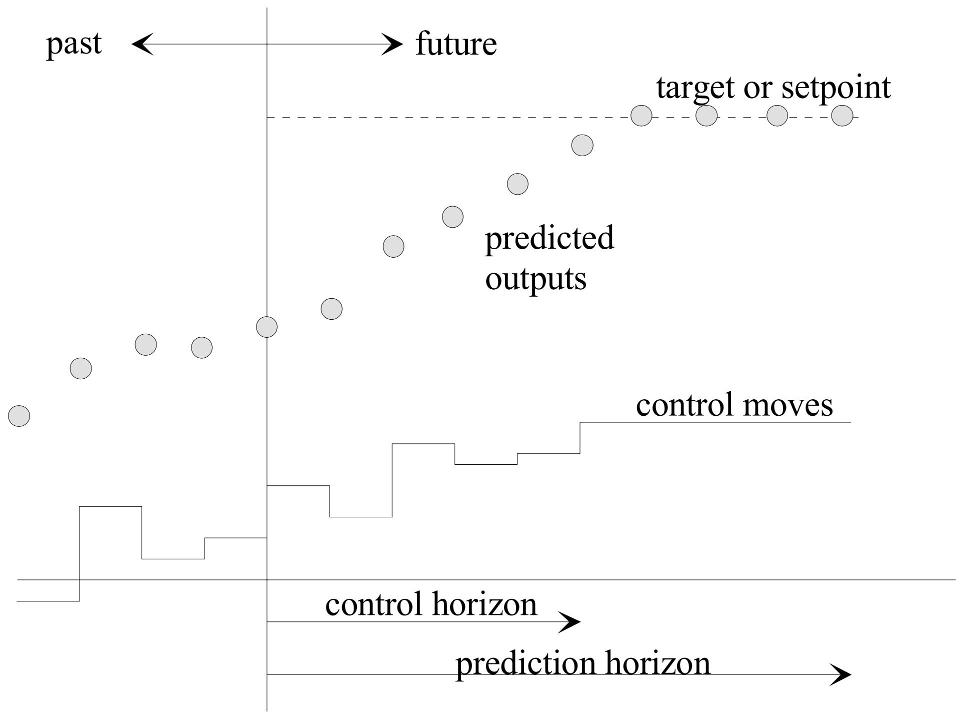


Figure 1: Prediction and control horizon of MPC.

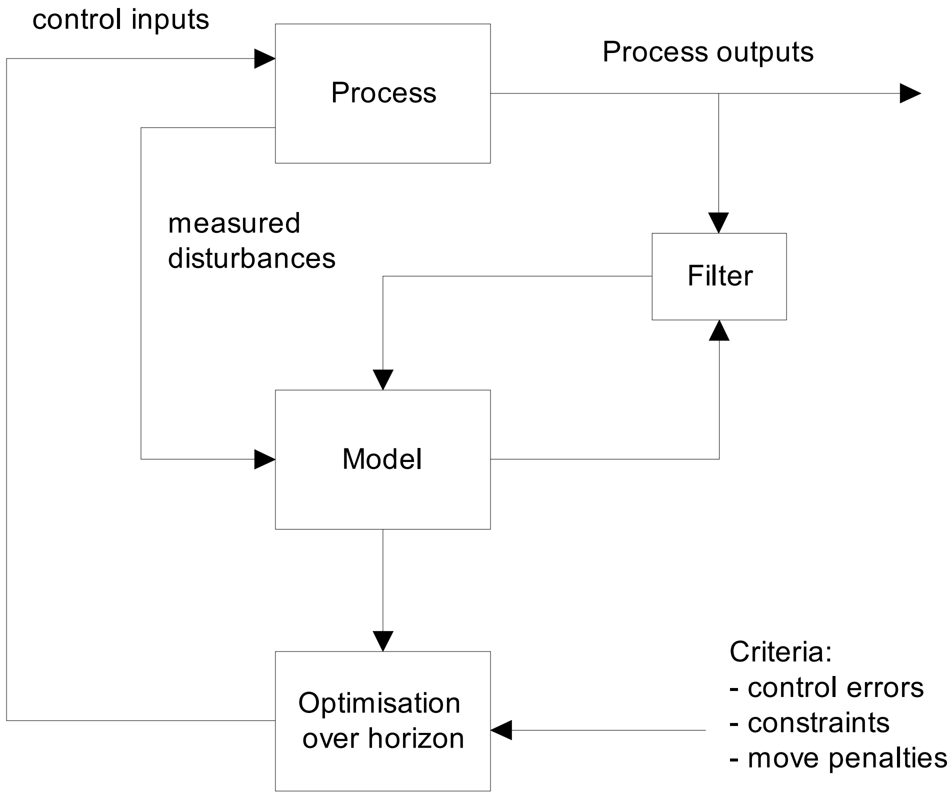
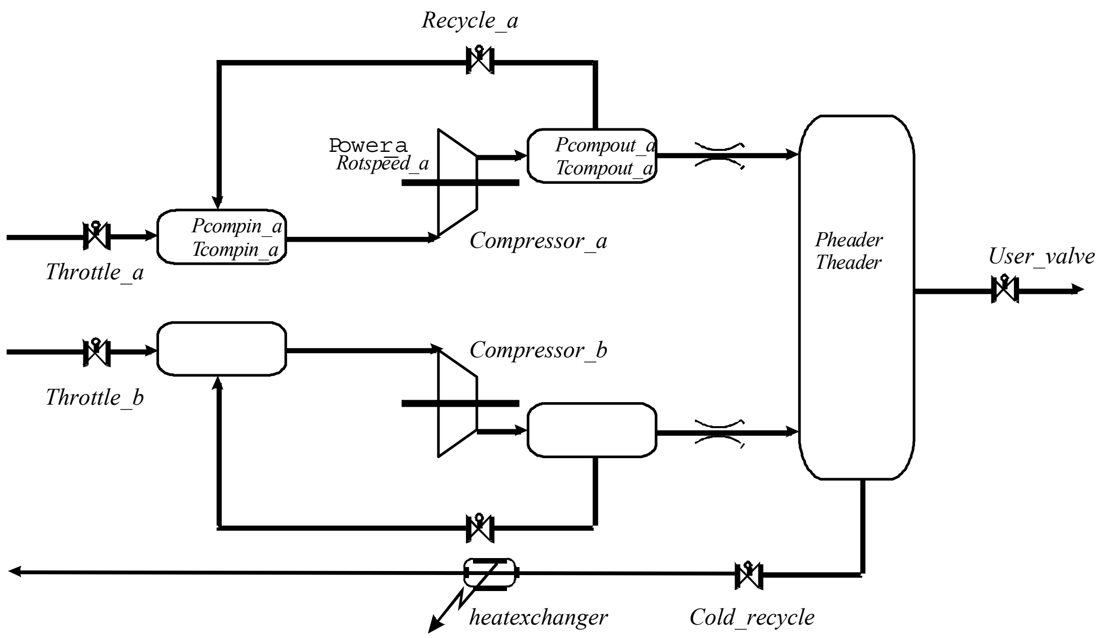


Figure 2: Basic diagram of a Model Predictive Controller (MPC).



Inputs:

1. Throttle-a
2. Recycle -a
3. Power-a
4. Throttle_b
5. Recyele-b
6. Power b
7. User valve
8. Cold Recycle-valve

Figure 3: Example compressor station used for the MPC study.

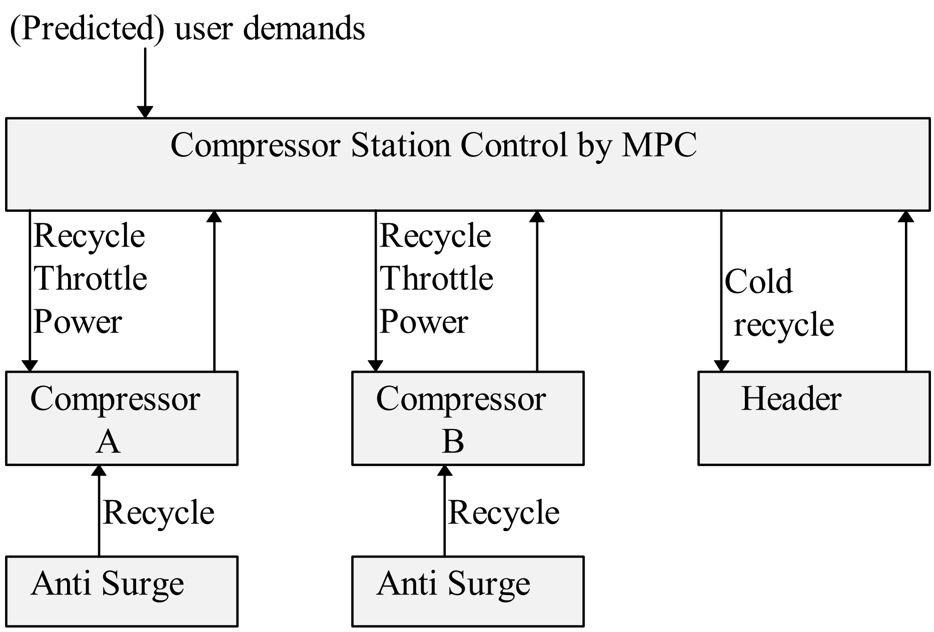


Figure 4: Control strategy for the compressor station.

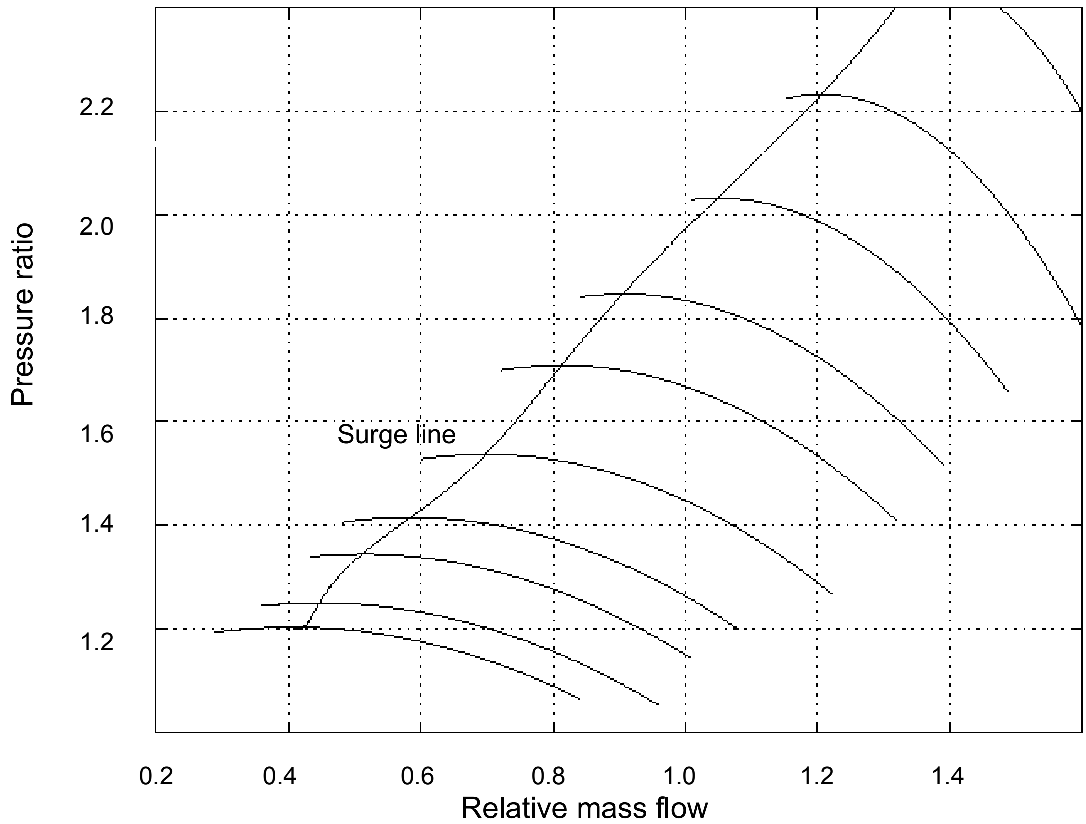
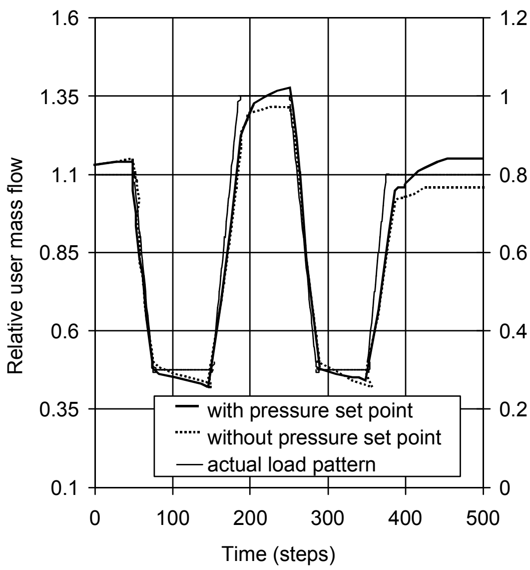
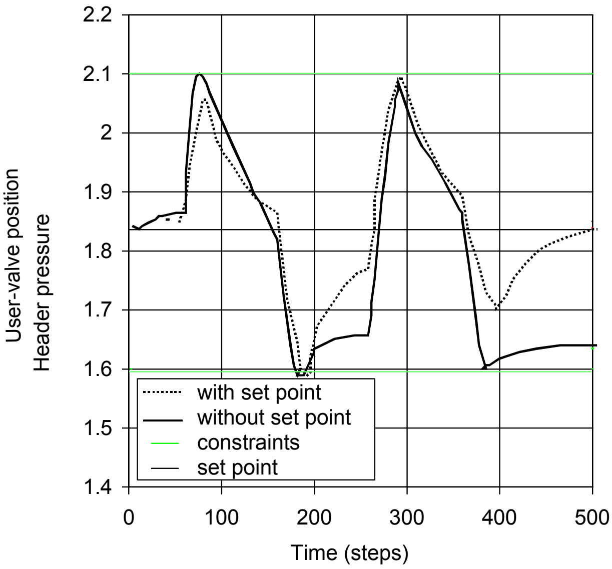


Figure 5: Compressor performance map at reference inlet conditions.

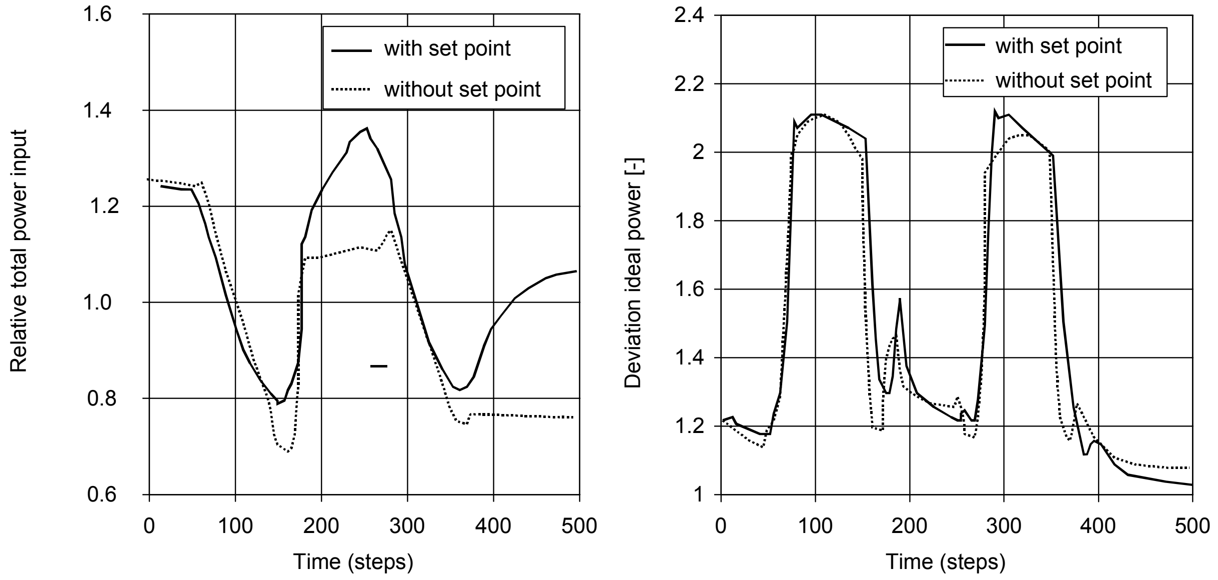


(a)



(b)

Figure 6: The responses of the mass flow to the user and the pressure in the header for a prescribed valve position with (a) and without (b) an additional set point on the header pressure.



(a) (b)

Figure 7: Total power input and power ratio for the simulations with (a) and without (b) a set point on the header pressure.

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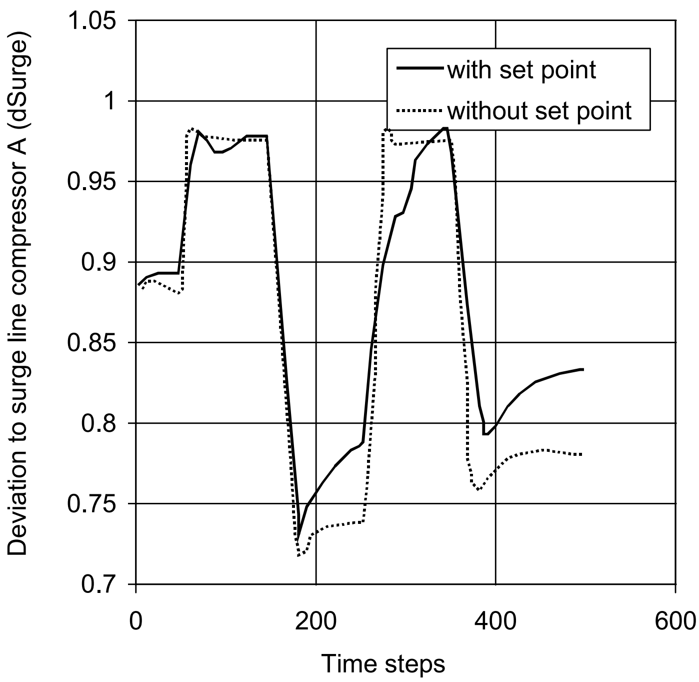

Figure 8: Surge avoidance by means of a constraint level on the distance to the surge line.