Mathias Scheel*, Andreas Berndt and Olaf Simanski

Model predictive control approach for a CPAP-device

A simulation study

Abstract: The obstructive sleep apnoea syndrome (OSAS) is characterized by a collapse of the upper respiratory tract, resulting in a reduction of the blood oxygen- and an increase of the carbon dioxide (CO_2) - concentration, which causes repeated sleep disruptions. The gold standard to treat the OSAS is the continuous positive airway pressure (CPAP) therapy. The continuous pressure keeps the upper airway open and prevents the collapse of the upper respiratory tract and the pharynx. Most of the available CPAP-devices cannot maintain the pressure reference [1]. In this work a model predictive control approach is provided. This control approach has the possibility to include the patient's breathing effort into the calculation of the control variable. Therefore a patient-individualized control strategy can be developed.

Keywords: CPAP, sleep apnoea, system modeling, model predictive control, fluid mechanics

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1 Introduction

A widespread sleep disorder is the obstructive sleep apnoea syndrome which has grown within recent years. The OSAS is characterized by a collapse of the upper respiratory tract, resulting in an increase of the CO_2 concentration and a reduction of the blood oxygen concentration, which causes repeated sleep disruptions as an automatic alarm function of the human body. If the disease is not treated, the risk of coronary thrombosis and apoplexy is heavily increased. The gold standard to treat the OSAS is the continuous positive airway pressure (CPAP) therapy. The continuous pressure keeps the upper airway open and prevents the collapse of the upper respiratory tract and the pharynx. The functionality of the CPAP-therapy is shown in Figure 1. The left picture shows an obstruction of the upper airway, while the right picture shows the opening of the upper respiratory tract as a result of the positive pressure. The main component

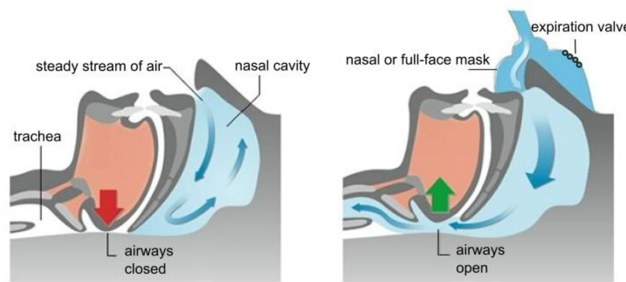

Figure 1: Functionality of the continuous positive airway pressure

of the CPAP-device is the centrifugal blower. The therapy tube and the breathing mask connect the device to the patient. An expiration valve is attached to the mask. The task of the valve is to prevent the CO_2 rebreathing and to allow a safe expiration.

During the spontaneous breathing of a patient, pressure and airflow change as a function of the breathing phase (inspiration and expiration). By the help of CPAP devices a permanent positive pressure is maintained to avoid a collapse of the upper airway. As a result of the patient's breathing pressure fluctuations occur in the mask. However, a constant pressure is necessary for the success of CPAP therapy.

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The influence of the breathing depends on the situational breathing effort (e.g. position of the patient) and on the physiological condition of the lung (resistance, compliance). To ensure a pleasant breathing the pressure deviation in the mask has to be within certain limits. By means of a standardized test procedure (s. DIN EN ISO 17510-1:2009-07) CPAP-device of known manufacturers were investigated and compared [1]. Corresponding to the test procedure 14-4 03/2007 MDS-Hi from the GKV-Medical Aids Register the pressure deviation between 4 hPa until 10 hPa pressure reference has to be less than 0.5 hPa - above 10 hPa pressure reference the limit is set to 1.0 hPa. The subdivision for sleep apnoea in the Association of Health Insurance actually claims a maximal pressure deviation of 0.6 hPa across all therapy pressure references [2]. Table 1 shows the pressure deviations of different CPAP-devices adjusted at a therapy pressure of 4 hPa [1].

Table 1: Pressure Deviation Δp of different CPAP-devices [1]

manufacturer	device	Δp in hPa
Weinmann	SOMNOcomfort	0.43
RESMED	Minni MAX nCPAP	0.50
HEINEN + LÖWENSTEIN	Somnia	0.54
HEINEN + LÖWENSTEIN	Somnia 2	0.54
FLOW	xPAP	0.57
Weinmann	SOMNOcomfort 2	0.57
RESPIRONICS	Somnia 2	0.67
RESPIRONICS	REMstart Pro M-Serie	0.74
RESMED	AutoSet	0.75
RESMED	S8 Elite	0.86
Fischer & Paykel	SleepStyle 200	0.90

It has been shown that many CPAP-devices cannot maintain the desired pressure set points. Only two (<= 0.5 hPa) or six (<= 0.6 hPa) devices fulfil the requirements. The objective of the present work is to reduce the pressure deviation in the mask. On the basis of a model of the breathing therapy system a model-based control approach was developed. Furthermore the breathing effort of the patient should be included into the control design to provide a patient-individual control approach. The developed control environment was tested in the modelling and simulation environment MATLAB Simulink.

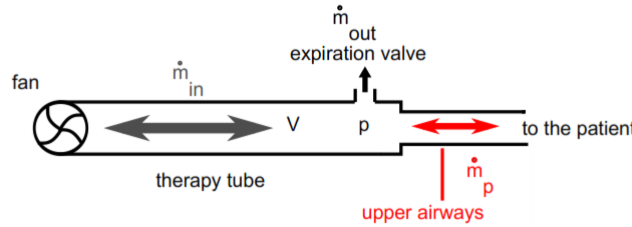

Figure 2: Representation of the pneumatic process

2 System modeling

In this section the model of the model-based control approach is introduced. As described in [3] and [4] the pneumatic system can be simplified as gas tank with inlet flow (system mass flow $\dot{m}_{in}$), outlet flow (leakage mass flow $\dot{m}_{out}$) and the flow to the patient (patient mass flow $\dot{m}_p$). Regarding to figure 2 the thermal equation of state is as follows:

$$pV = mR_sT \tag{1}$$

in which pressure p, volume V, temperature T, mass m and specific gas constant R_s is described. Assuming that the process is isotherm, equation (1) can be solved into a differential equation by time-derivation of the values p and m. By inserting the mass balance of the three mass flows follows:

$$\dot{p} = \frac{R_sT}{V}\dot{m}_{in} - \frac{R_sT}{V}\dot{m}_{out} - \frac{R_sT}{V}\dot{m}_p \tag{2}$$

The calculation of the leakage mass flow $\dot{m}_{out}$ can be carried out by ROHRER's equation [5]. The solution of the quadratic equations results in:

$$\dot{m}_{out} = -k_a \pm \sqrt{k_b + pk_c} \tag{3}$$

The aim of the CPAP-therapy is to maintain the pressure at a constant value. Thus, equation (3) can be approximated by a linear equation at the operating point p_{op}.

$$\dot{m}_{out} = \frac{k_c}{\sqrt{k_b + p_{op}k_c}}p = k_{out}p \tag{4}$$

The patient as the second pneumatic systems is modelled hereafter. As a simple model approach the upper respiratory tract and the lung can be described as a resistance R and a capacity C connected in series [6, 7]. The capacity describes the lung compliance, i. e. the proportion of the extendibility due to the pressure in the lung. The breathing propulsion, which is usually generated by the movement of the diaphragm, is modeled as a second pressure source p_{musc}.

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The relationship between the input $\dot{m}_p$ and the output variable p can be derived:

$$
\begin{aligned}
p &= \frac{\dot{m}_p}{\rho} R + \frac{1}{C} \int \frac{\dot{m}_p}{\rho} dt + p_{musc} \\
\ddot{m}_p &= \frac{\rho}{R} (\dot{p} - \dot{p}_{musc}) - \frac{1}{RC} \dot{m}_p
\end{aligned} \tag{5}
$$

These can also be formulated as a second order state space model with the following parameter. This model description can easily be used for the model-based control approach.

$$
\begin{aligned}
a_{11} &= -k_p k_{out} & a_{12} &= -k_p \\
a_{21} &= -\frac{\rho}{R} k_p k_{out} & a_{22} &= -\frac{1}{RC} - \frac{\rho}{R} k_p \\
b_1 &= k_p & b_2 &= \frac{\rho}{R} k_p \qquad e_2 = -\frac{\rho}{R}
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
\begin{bmatrix} \dot{p} \\ \ddot{m}_p \end{bmatrix} &= \begin{bmatrix} a_{11} & a_{12} \\ a_{12} & a_{22} \end{bmatrix} \begin{bmatrix} p \\ \dot{m}_p \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} \dot{m}_{pin} + \begin{bmatrix} 0 \\ e_2 \end{bmatrix} p_{musc} \\
p &= \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ \dot{m}_p \end{bmatrix}
\end{aligned} \tag{7}
$$

3 Control approach

3.1 Overall control environment

Based on the results from [4] a four-stage cascaded control environment was used. The presentation of the cascade is shown in figure 3. In [3] a state space controller with pole-placement method was developed. In this work another

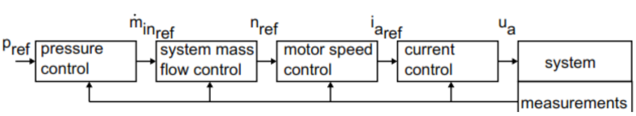

Figure 3: Schematic of the four-stage cascaded control environment

model-based control approach is provided. The model predictive control is introduced in the next section.

3.2 Model predictive control

In contrast to state space control with pole-placement method, the aim of the model predictive control (MPC) strategy is to minimize a given quality criterion. According to [8, 9, 10] the control law was calculated by minimizing the quality criterion

$$
\begin{aligned}
J = {} & [Y(k+1) - Y_R(k+1)]^T Q [Y(k+1) - Y_R(k+1)]^T + \\
& \Delta U(k)^T R \Delta U(k) + E(k)^T \alpha E(k)
\end{aligned} \tag{8}
$$

The solution of the quality criterion (8) results in:

$$
\begin{aligned}
\Delta u(k) &= [1, 0, \dots, 0] \Delta U(k) \\
&= K Y_R(k+1) - K_x x(k) - K_u u(k-1) - K_z z(k)
\end{aligned} \tag{9}
$$

with,

$$
\begin{aligned}
K' &= [1, 0, \dots, 0]^T (H^T Q H + R + H_e^T \alpha H_e)^{-1} \\
K &= K' H^T Q \\
K_x &= K' (H^T Q F + \alpha H_e^T F_e) \\
K_u &= K' (H^T Q G + \alpha H_e^T G_e) \\
K_z &= K' (H^T Q Z + \alpha H_e^T Z_e)
\end{aligned} \tag{10}
$$

The matrices H, H_e, F, F, G , G_e, Z and Z_e were built with the extended and discretizied state space model based on equation (7). The matrices Q and R and the factor α are the adjustable parameters for the MPC-design.

4 Control results

First of all the developed control strategy was simulated in MATLAB Simulink. Therefore all developed subsystems were implemented, parameterized and the four-stage cascade were designed. The impact of the breathing effort could be adjusted by the breathing frequency, I:E relationship and the maximal inspirations and expiration pressure. To simulate a natural breathing, besides the sinusoidal breathing eff ort, the course was designed with more sinusoidal parts. An example

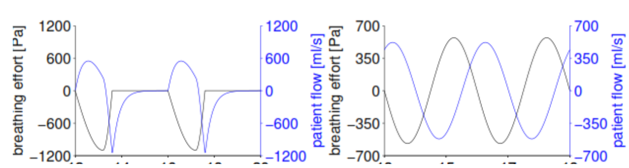

Figure 4: Exemplary course of the breathing effort: left – natural : right – sinusoidal breathing

is shown in figure 4. This adjustments can also be done at a lung simulator like the *ASL 5000 Breathing Simulator*. In the simulation tests with diff erent patient models with and without considering the breathing eff ort were investigated. The breathing eff ort was always adjusted to simulate a tidal volume of 500 ml. Figure 5 shows the mask pressure without and with considering the breathing eff ort. The pressure

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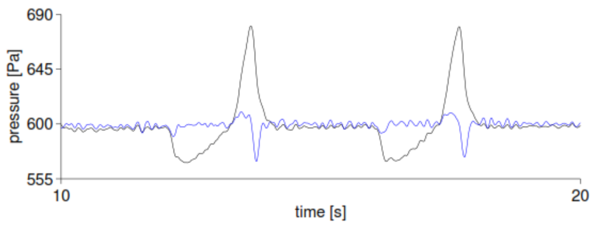

Figure 5: Exemplary course of the mask pressure with natural breathing: black – without breathing effort: blue – with breathing effort

deviation could be reduced from 1.12 hPa to 0.41 hPa. The dynamic of the control strategy was adjusted to provide a noise in the control variable (motor voltage) not more then 2% of the dynamic range of the motor supply voltage. Furthermore the pressure deviation without considering the breathing eff ort has to be around 1.2 hPa. The investigation of diff erent CPAPdevices demonstrate a pressure deviation of ca. 1.2 hPa if the breathing was imitated with a lung simulator and a natural breathing (s. Figure 4 -left). Table 2 shows the pressure deviation of diff erent test scenarios – with
natural breathing and sinusoidal breathing and diff erent RC combinations. In all test scenarios the control quality could be improved when considering the patient's breathing eff ort.

Table 2: Pressure Deviation Δp of different test scenarios – R[cmH20/l/s], C [ml/cmH20]

scenario	Δp in hPa without p_{musc}	Δp in hPa with p_{musc}
natural – R = 6 C = 50	1.12	0.41
natural – R = 30 C = 50	1.07	0.50
natural – R = 6 C = 10	1.30	0.74
sinus – R = 6 C = 50	0.60	0.11
sinus – R = 30 C = 50	0.70	0.25
sinus – R = 6 C = 10	0.43	0.12

5 Discussion

The presented control strategy gives a further possibility for a model-based control approach. With a model predictive control approach the pressure deviation could be reduced if considering the patient's breathing eff ort.

This simulative investigation of the developed model predictive control approach provides significant improvement of the control quality. Further investigations for the evaluation of the control quality considering parameter variations and errors in the estimation of the breathing eff ort are necessary.

In additional steps the simulation shall be put into practice and the control quality shall be examined again. Due to more estimation and simplification errors in practice the advantage of the MPC is less – as the case may be the controller parameters has to be adjusted and sources of errors have to be reduced.

Author's Statement

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