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Adaptive control for compensation of non-linear hose characteristics in mechanical ventilation

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Summary. Mechanical ventilators are medical devices used to assist patients to breathe. The aim of this paper is to develop a control approach that compensates the pressure drop over the hose that connects the ventilator to the patient. In [1], a similar strategy is considered assuming a linear system model, which is valid in a small operating range. To achieve the desired performance in the entire operating range, the quadratic nature of the resistance of an actual hose is considered in this paper. Using a quadratic hose model and a recursive least-squares estimator, the control law proposed in [1] is significantly improved. Through an experimental case study, a significant gain in pressure tracking performance is shown.

Background

Mechanical ventilation is commonly used in Intensive Care Units (ICUs) to save lives of patients who are unable to breathe by themselves. To assist these patients a mechanical ventilator is used. A schematic overview of a mechanical ventilator, with a single-hose setup, and a patient is depicted in Figure 1.

In this paper, the ventilation setup as depicted in Figure 1 and Pressure Controlled Ventilation (PCV) of sedated patients is considered. In PCV, the goal is to ensure that the pressure near the patients airway, i.e., p_{aw}, follows a reference as shown in Figure 2. This reference has two different pressure levels to ensure that air flows in and out of the lungs. Therewith, inspiration and expiration of the patient are supported. In practice, damage to the lung tissue should be prevented, e.g., by overshoot in pressure. Therefore, the pressure tracking performance should be accurate.

Previous work and open challenges

The control goal is to ensure that the airway pressure p_{aw}, see Figure 1, tracks the target pressure p_{target}. This is achieved by controlling the blower outlet pressure p_{out}. The airway pressure near the patient's mouth is defined as $p_{aw} = p_{out} - \Delta p$, with Δp the pressure drop over the hose. In [1], a novel adaptive control law is proposed that compensates for this pressure drop. A block scheme of this control law is shown in Figure 3. During ventilation, a linear hose resistance, i.e., $\hat{R}_{lin}$, is estimated using a recursive least-squares estimator. This estimate in combination with the measured flow is used to compute an estimate of the pressure drop over the hose, i.e., $\Delta\hat{p} = \hat{R}_{lin} Q_{out}$. Then, $\Delta\hat{p}$ is used to increase the blower outlet pressure, i.e., $p_{out} = p_{target} + \Delta\hat{p}$. Theoretically, this results in perfect tracking, independent of the patient, leak, or hose parameters, for time-varying target pressures.

Although the results in [1] are promising for use-cases with relatively small flow variations, in an experimental case study it is observed that for large flows performance deteriorates. This is caused by the typically non-linear hose characteristics, see Figure 4. This figure shows that the linear model 1 is an accurate representation of the hose resistance for the low flow regime. However, for large flow variations the linear models show a significant deviation from the measured values. It is clearly shown that a quadratic hose model is a better representation of the measured hose characteristics. This quadratic hose model is defined as follows:

$$\Delta p = R_{lin} Q_{out} + R_{quad} Q_{out} |Q_{out}|, \tag{1}$$

where R_{lin} and R_{quad} are unknown. Combining this non-linear hose resistance model with a linear model for the patient lung dynamics results in a non-linear dynamical model of the patient-hose system. The exact model is omitted for brevity. In the following sections, it is shown how the quadratic hose parameters are estimated online and, subsequently included in the control law to accurately compensate for the pressured drop over the hose and therewith improve performance.

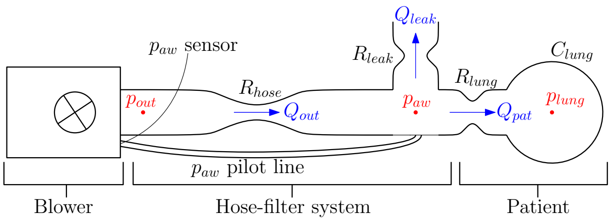


Figure 1: Schematic representation of the blower-hose-patient system of the considered ventilation system.

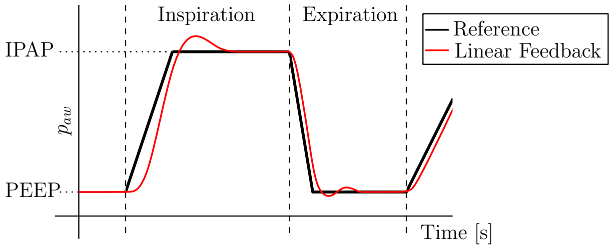


Figure 2: Airway pressure (p_{aw}) during one breathing cycle of pressure controlled ventilation.

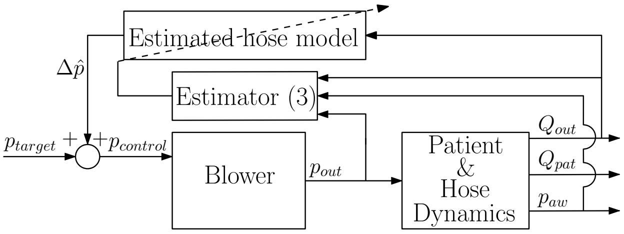


Figure 3: Block diagram of the considered control approach.

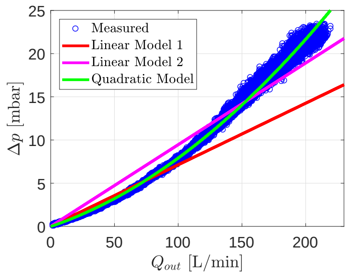


Figure 4: Quadratic characteristics of a typical hose system.

Proposed control strategy

In this paper, the following quadratic-hose model is included in the control law depicted in Figure 3:

$$\Delta\hat{p} = \hat{R}_{lin}Q_{out} + \hat{R}_{quad}Q_{out}|Q_{out}|. \tag{2}$$

To complete the adaptive control law an estimator is used to obtain estimates $\hat{R}_{lin}$ and $\hat{R}_{quad}$ of the two hose parameters. These parameters are obtained using a Recursive Least Squares (RLS) estimator with exponential forgetting factor, see [2]. The considered estimator dynamics are given by:

$$\dot{\hat{\theta}}(t) = P(t)\frac{\Delta p(t) - \hat{\theta}(t)\phi_0(t)}{m^2}\phi_0(t), \text{ and } \dot{P}(t) = \beta P(t) - P(t)\frac{\phi_0(t)\phi_0^T(t)}{m^2}P(t), \tag{3}$$

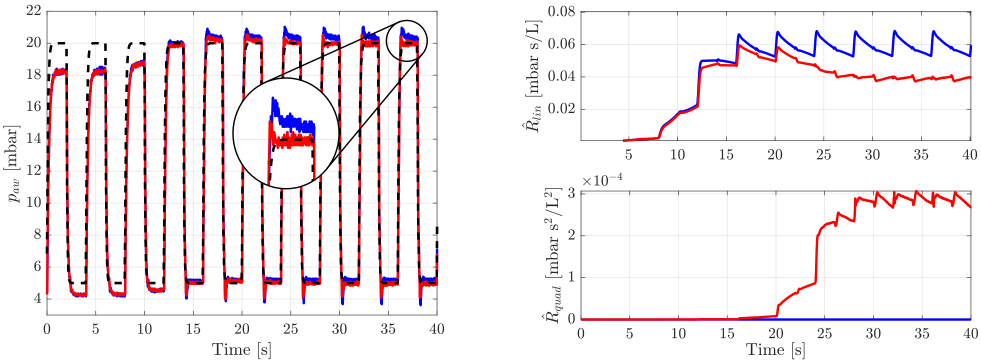
where $\hat{\theta}(t) = \begin{bmatrix}\hat{R}_{lin}(t)\\ \hat{R}_{quad}(t)\end{bmatrix}$, $\Delta p(t) = p_{out}(t) - p_{aw}(t)$, $P(t) = \begin{bmatrix}P_{11}(t) & P_{12}(t)\\ P_{21}(t) & P_{22}(t)\end{bmatrix}$, $\phi_0(t) = \begin{bmatrix}Q_{out}(t)\\ Q_{out}(t)|Q_{out}(t)|\end{bmatrix}$, m is the scalar normalization parameter, and β is the scalar exponential forgetting factor.

Experimental results

The overall approach is implemented on an experimental ventilation setup, schematically depicted in Figure 1, and the obtained results are shown in Figures 5a and 5b. In Figure 5a, it is clearly seen that the tracking performance upon convergence is improved significantly. Furthermore, Figure 5b shows that the oscillations in the estimates are reduced. Concluding, performance is significantly increased by compensating for the non-linear hose characteristics.

Conclusions

This paper clearly shows that extending the adaptive control strategy in [1] with a non-linear (quadratic) hose model can significantly improve pressure tracking performance. This means that pressure support of mechanically ventilated patients can be improved by compensating for the non-linear hose characteristics.



(a) Resulting airway pressure of the controller in [1] and the controller of this paper.

(b) Resistance estimates of (1), using the controller in [1] and the controller of this paper.

Figure 5: Experimental results showing the tracking performance and estimated parameters of the controller proposed in [1] (—) and the controller proposed in this paper (—). Clearly showing improved tracking of the reference pressure (- - -) by including the non-linear hose characteristics.

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[2] P.A. Ioannou and J. Sun, "Robust Adaptive Control". Upper Saddle River, NJ: Prentice-Hall, 1996.