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SIMULATION-BASED DESIGN OF AN ENERGY-EFFICIENT VACUUM CONTROL OF A MILKING MACHINE

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Abstract: *The pulsating vacuum level of milking machines has to follow a well-defined profile. Conventionally, the vacuum is supplied by a pump running at nominal speed. To control the vacuum a servo valve is opened to ambient air. This paper describes the development of a new cascaded vacuum control by the pump speed. The energy consumption is reduced because of the avoided valve losses and a more efficient engine operation. The control strategy was developed in a mechatronic approach based on the simulation of the entire plant including the fluid dynamics of the vacuum system.*

Key words: *fluid dynamics, simulation, milking machine*

1. INTRODUCTION

In milking plants the milk removal from the cow's udder is stimulated by the pulsating flow of ambient air and vacuum in teat-cups between the flexible rubber liners and the shells. The vacuum level is crucial for animal welfare and health. The effects of the vacuum on milk yield, teat condition, and udder health are described in (Rasmussen et al., 2000). In (Reinemann et al., 2003) an overview of research activities in milking machine research is given.

During the milking process the vacuum level has to follow a given profile within well-defined tolerances (ISO 5707, 1996). Disturbances e.g. by animals kicking off milking liners or due to leakage during applying the teat cup liners must be compensated. In general, the vacuum pump is running at a nominal rotation speed. The vacuum level is adjusted by means of a servo-valve in the vacuum system which can be opened to ambient air. The pump and the engine are operated with an unnecessary high power in an energy-inefficient way. Furthermore the possibilities for improving the disturbance reaction of the control loop are restricted.

The research work (Voicu et al., 2009) presented in this paper aims to improve the vacuum quality in an interdisciplinary mechatronic approach. The control of the vacuum by the servo-valve is replaced by a new cascade control including an inner control loop of the rotational pump speed. The development of the control strategies was carried out based on a simulation model of the plant. The model was validated at a test bed. The control structure is shown in fig. 1. It includes the frequency converter, asynchronous motor (ASM), the pump and the vacuum system consisting of the various pipes and volumes such as vacuum tank, milk receiver jar, pulsator, milk hose, claw and teat-cup.

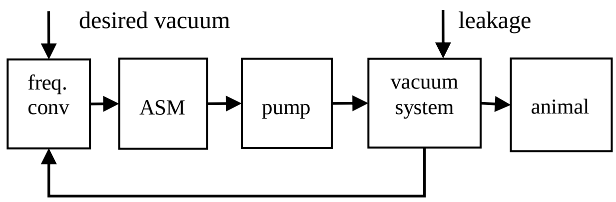

Fig. 1. Basical control structure of the milking machine

2. MODELLING AND SIMULATION

The mathematical model of the vacuum system can be derived from the conservation principles of fluid mechanics for mass, impulse, and energy (Rist, 1996). A set of partial differential equations for the pressure p, temperature T and flow velocity w depending on time and position is obtained for each pipe of the vacuum system. Measurements at the test bed (Voicu et al., 2009) have shown that the temperature in the vacuum system is almost constant. Thus the energy conservation equation can be neglected to simplify the mathematical model. This leads to a set of differential equations (1) and (2) for each pipe of the vacuum system. The pressure p and the flow velocity w are given as a function of time t and position x in one dimension taking into account losses due to friction and shape:

$$\frac{\partial p}{\partial t} = -w\frac{\partial p}{\partial x} - \kappa \cdot p \cdot \frac{\partial w}{\partial x} + (\kappa - 1) \cdot \left(\frac{\lambda \cdot w^2 \cdot |w| \cdot p}{2 \cdot R_i \cdot T \cdot D} \right) \quad (1)$$

$$\frac{\partial w}{\partial t} = -w\frac{\partial w}{\partial x} - \frac{R_i \cdot T}{p}\frac{\partial p}{\partial x} - \frac{\lambda \cdot w \cdot |w|}{2 \cdot D} \quad (2)$$

The constants κ, R_i, λ and D denote the adiabatic exponent, specific gas constant, pipe friction coefficient and diameter. The local dependency is discretised by introducing difference quotients instead of local derivatives. This yields ordinary non-linear differential equations. Special attention has to be paid to the boundary conditions at bifurcations (Voicu et al., 2009).

For the overall model the vacuum pump, engine and frequency converter have to be described, too. The pump is modelled by the static characteristic diagrams of volume flow and performance. The model is implemented under Matlab/Simulink as a modular library that can easily be adapted to different configurations of milking machines. The simulation results were successfully verified based on the milking machine in the test bed and on two other milking machines operating under practical conditions on farms.

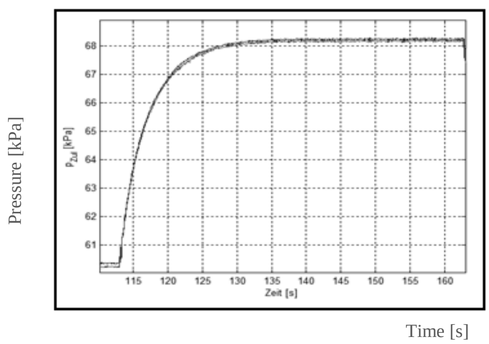

Fig. 2. Comparison of simulation results and pressure measurements

Fig. 2 shows a good correlation between the measurement of the pressure in the supply air pipe with constant rotational pump speed and simulation results of the test bed. The step response of the vacuum system was simulated by opening a teat-cup and the pressure in the pipelines is increasing 8 kPa in 22 seconds.

3. TEST BED

In cooperation with an industrial partner a test bed with 16 milk units was built consisting of exchangeable combinations of different asynchronous motors and pumps, a frequency converter, and the vacuum system of the milking machine as shown in fig. 3. The milking process consists of repeatedly opening (milk phase) and closing (massage phase) the teat-cup liner. As the pulsator operates, it causes the chamber between the shell and the liner to alternate regularly from vacuum to air source.The end of the cow's teat is exposed to the vacuum and the internal milk pressure within the cow's udder causes the milk to be drawn out through the teat opening. From the pipelines, milk flows by gravity into a receiver jar. A milk pump removes the milk from the receiver jar and it transfers it to the bulk tank. A vacuum regulator is located in the vacuum supply pipe between the vacuum reserve tank and the sanitary trap which supplies the receiver jar with vacuum.

To analyse the functionality of the test bed, sensors for measuring pressure, mass flow rate and temperature at various points were installed in the pipelines.

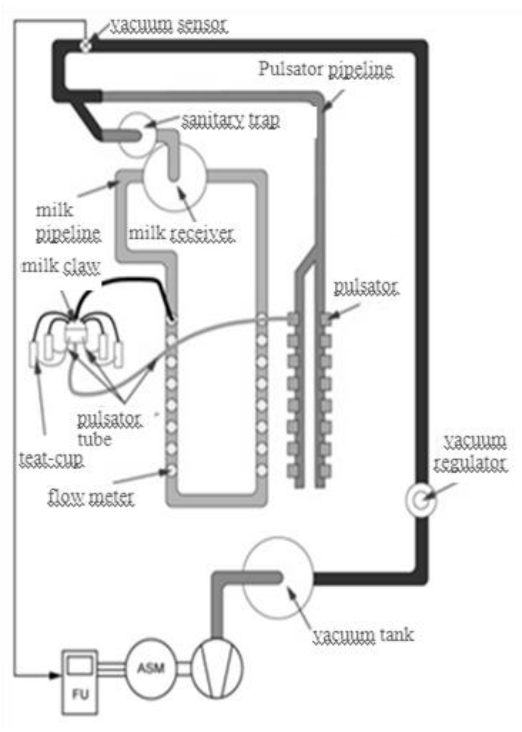

Fig. 3. Milking machine

4. CONTROL DESIGN

The simulation model was used to develop a new multi-loop vacuum control of the milking machine (Popić, 2009). In a first step, the inner feedback loops have been designed with classical methods in frequency domain. Due to the nonlienarities of the plant the outer vacuum control loop was developed in an empirical approach by means of simulations. The vacuum control loop was optimized towards the reaction to disturbances such as sudden leakages in the vacuum system. The control algorithms were evaluated both in simulation and in experiments in the test bed. In fig. 4 the reaction of the control loop to droping off and reapplying a set of milking liners is depicted. The simulation results show a good analogy to the measured test result.

As an important outcome of simulation and experiments the performance of the vacuum control is mainly restricted by the limits of the actuating variable of the frequency converter.

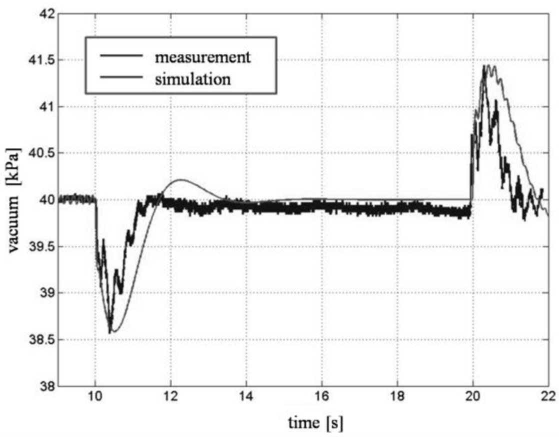

Fig. 4. Disturbance reaction of the vacuum control loop

6. SUMMARY AND CONCLUSIONS

The simulation-based development of a new cascaded vacuum control for milking machines via the rotational speed of the vacuum pump has been described. It avoids energy-inefficient control interventions of the servo valve in the vacuum pipe. The simulation model includes the vacuum pump, the engine and the frequency converter as well as the fluid dynamics of the vacuum system. The local dependency in the partial differential equations of the pressure and flow velocity could be discretized to obtain ordinary differential equations. The simulation model was validated by measurements at an experimental milking machine. The control algorithms were evaluated both in simulation and in experiments. As a result it could be shown, that the performance of the vacuum control is restricted by the limits of the actuating variable of the frequency converter.

7. ACKNOWLEDGEMENTS

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