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USE OF NI LABVIEW AND DAQ SOLUTION FOR CONTROLLING THE VACUUM LEVEL IN A MECHANICAL MILKING MACHINE

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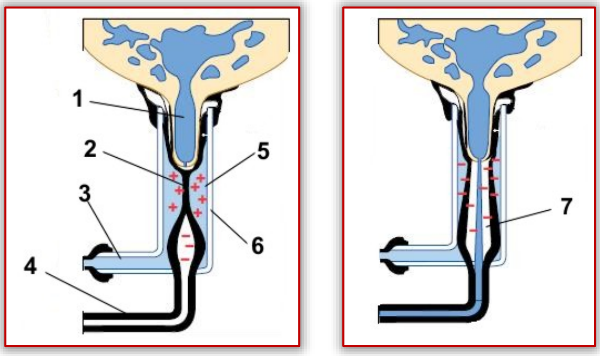
Abstract: The VFD technology is able to adjust the rate of air removal from the milking system by changing the speed of the vacuum pump motor. Based on the NI LabView 7.1 software and the USB 6009 DAQ board a PID controller was developed in order to control the electric motor driving the vacuum pump. The PID controller was tuned using the Ziegler-Nichols tuning rules for the frequency response method, based on preliminary tests performed over the milking system. Another series of comparative tests aimed to evaluate the operating parameters of the milking system (pulsation rate and ratio, duration of the pulsation phases) and vacuum stability, for different vacuum levels. The tests showed that vacuum regulation by the means of the PID controller did not adversely affect the working parameters of the system, while achieving better results regarding the stability of the permanent vacuum.
Keywords: VFD, mechanical milking, permanent vacuum, vacuum regulator, significance level

INTRODUCTION

The mechanical milking is achieved due to the vacuum applied to the teat by the means of a teatcup. In order to limit the development of congestion and edema and provide relief to the teat from the milking vacuum, the pulsation principle is used (Mein et al., 1987). As shown in Figure 1, vacuum is applied to the teat through the vacuum chamber (7) created inside the liner (2). The collapse of the teatcup liner (2) beneath the teat is achieved when air at atmospheric pressure is admitted into the pulsation chamber (5) of the teatcup (Figure 1a); the liner opens, allowing the extraction of milk, when vacuum is applied to the pulsation chamber (Figure 1b).

The importance of vacuum level and stability is given by the fact that cows have a biological limit for a positive reaction to vacuum and exceeding it may lead to damage of the teat tissue or slipping of milking clusters off the teat, resulting in an extended milking time and in improper milking; vacuum fluctuations generated within the milking cluster may lead to direct bacterial penetration, thus causing mastitis (Pařilová et al., 2011).

In a typical mechanical milking system (Figure 2) vacuum is created by the vacuum pump (2), driven by an electric motor (1). The vacuum level is regulated by the means of the vacuum regulator (4), placed downstream of the receiver. The vacuum pump operates permanently at full capacity, providing a flow of air greater than the one entering the system through pulsators, claws, leaks. When working vacuum increases above the desired level (lower absolute pressure) the vacuum regulator opens, allowing supplementary air to enter into the system; when vacuum decreases below the necessary value (higher absolute pressure) the regulator closes. According to the ISO 5707:2007 standard the working vacuum should be maintained within ±2 kPa of the nominal vacuum.



(a) (b)

Figure 1 - The principle of milk extraction (adapted from Tetra Pak Dairy Processing handbook, 1995)
a-massage; b-milk extraction; 1-teat; 2-liner; 3-short pulse tube; 4-short milk tube; 5-pulsation chamber; 6-shell; 7-vacuum chamber.

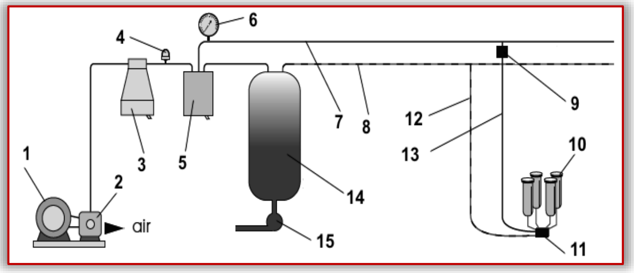


Figure 2 - Layout of a mechanical milking system.
1-electric motor; 2-vacuum pump; 3-interceptor; 4-vacuum regulator; 5-sanitary trap; 6-vacuum gauge; 7-permanent vacuum pipeline; 8-milk pipeline; 9-pulsator; 10-teatcup assembly; 11-claw; 12-long milk tube; 13-long pulse tube; 14-receiver; 15-milk pump.

In order to make the vacuum pump draw only the amount of air needed to maintain the desired vacuum level, thus decreasing the energy consumption of the electric motor, the speed of the pump should be variable; in this case no conventional regulator is needed to maintain the imposed vacuum during milking. The electric motor of vacuum pump is controlled by the means of a variable frequency driver (VFD). This solution has the potential to significantly reduce the energy consumption of the milking system; in a study conducted by Pazzona et al. (2003) energy savings between 24 and 87% were reported. It was concluded that, if the VFD controller is adjusted properly, it can meet or even exceed the vacuum stability recorded by the systems equipped with conventional regulators (Pazzona et al., 2003; Reinemann, 2005), the target being a receiver vacuum within ±2 kPa of the vacuum set point during normal milking (ISO 5707:2007).

The vacuum regulation method presented in this paper is based on the National Instruments solutions for hardware and software: a virtual instrument (vi) was used to emulate a PID (Proportional-Integral-Derivative) regulator in order to control the VFD which drives the electric motor of the vacuum pump. The PID regulator was emulated within the NI LabView 7.1 programming environment; the vacuum level was fed into the computer and the electric signal from the regulator was fed to the VFD by the means of the NI USB 6009 aquision board. Dry tests were performed in order to establish the adequate values of the parameters of the PID controller and to evaluate the vacuum stability and operating parameters of the system with the vacuum pump running at a variable speed.

MATERIAL AND METHOD

A bucket type milking machine was tested; Figure 3 presents the diagram of the developed milking machine and control system. The original system was equipped with a valve and spring type of vacuum regulator, placed on the pipeline connecting the interceptor (I) to the bucket (B); the electric motor (M) driving the vacuum pump (VP) was connected to the three phase power grid through the variable frequency drive (VFD). A BRK type pneumatic pulsator (P) was used to achieve the liner pulsation; the machine was equipped with four Boumatic R-1CX type teatcups. Artificial teats, manufactured according to the ISO 6690:2007 standard, were inserted into the teatcups. The vacuum pump provided an airflow $q=4.69 \cdot 10^{-3}$ m^3 s^{-1} at a speed of 1350 min^{-1}.

In order to use the VFD controller for driving the vacuum pump a Smartec SPD015AAsil absolute pressure sensor (T, Figure 3) was used to monitor the vacuum in the permanent vacuum line, providing the pressure signal for the VFD controller. The electric signal from the pressure sensor was fed to the data acquisition (DAQ) board by the means of an adequate signal conditioning unit (SC).

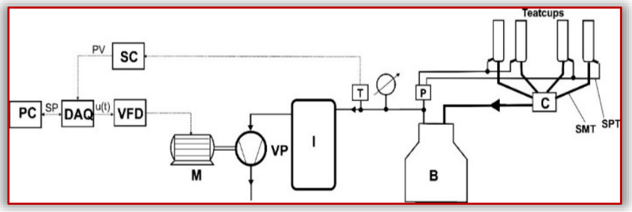


Figure 3 - Schematics of the milking system
DAQ-data aquision board; SC-signal conditioning unit; I-interceptor; VP-vacuum pump; M-electric motor; B-bucket; P-pulsator; SMT-short milk tube; SPT-short pulse tube; T-absolute pressure transducer; C-claw.

The data aquision board was USB 6009 (National Instruments), with a sample rate of 48 ksamples/s, four differential analog input channels and two analog output channels.

Based on the software running on the computer the entire system (DAQ board, VFD controller and computer) was acting as a PID regulator for the vacuum level, for which the set point (SP) is the desired vacuum level and the process variable (PV) is the actual vacuum level in the permanent vacuum pipeline. The controller delivers the output signal u(t) (Figure 4), which is then used to command the VFD and adjust the running speed of the electric motor and vacuum pump. The PID controller output is given by the relation (Aström and Murray, 2008):

$$u(t) = K_p \cdot \left[e(t) + \frac{1}{T_i} \cdot \int e(t) \cdot dt + T_d \cdot \frac{de(t)}{dt} \right], \qquad ((1)$$

where the error signal is e(t) = SP-PV; K_P is the proportional gain, T_I is the integral time and T_d is the derivative time.

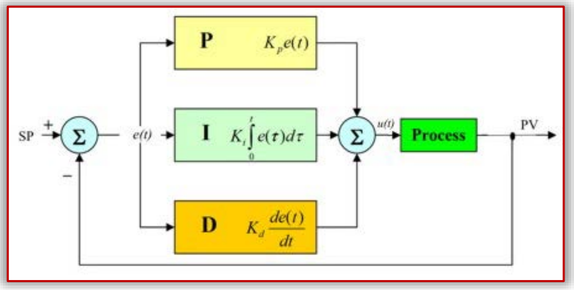


Figure 4 – Layout of a PID Regulator
$K_i = K_p/T_i$;; $K_d = K_p \cdot T_d$.

The PID controller was developed using the PID control toolbox from LabVIEW 7.1; a virtual instrument was created in order to manipulate the PID controller and provide the adequate control signal to the VFD. Figure 5 presents the block diagram of the virtual instrument and the control panel of the virtual instrument is shown in Figure 6. The control panel allowed the adjustment of the desired vacuum level (vacuum set point) and of the PID gains: proportional gain, integral time [min] and derivative time [min]. An oscilloscope display allowed the visualization of the vacuum set point, system vacuum and output signal of the PID controller.

As the analog output range of the USB 6009 data aquision board is 0-5 V, an additional signal conditioning unit, based on an operational amplifier (not shown in Figure 3) was used to boost the PID signal in order to obtain the 0...10V range accepted by the variable frequency drive.

The variable frequency drive unit was VFD 007M43B (0.7 kW maximum power of the electric motor); the output frequency range was set to 0...60 Hz for a 0-10 V range of the analog comand signal (Delta Electronics, 2008).

In order to establish the operating parameters during mechanical milking process (pulsation rate and ratio, duration of the phases), two additional Smartec SPD015Aasil absolute pressure sensors (not shown on the diagram in Figure 3) were attached to the short pulse tube (SPT, Figure 3) and short milk tube (SMT). The pulsation ratio was defined according to the specifications of the ISO 5707:2007 standard.

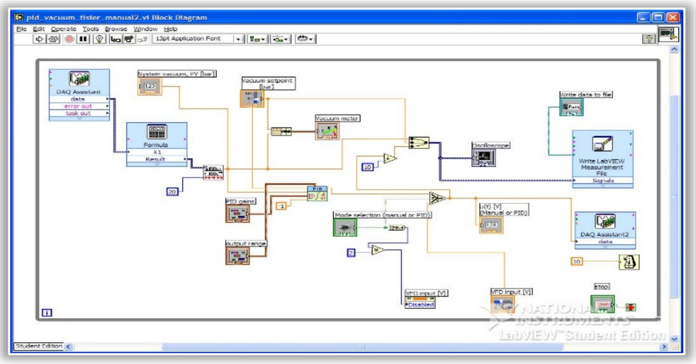


Figure 5 – Block diagram of the virtual instrument

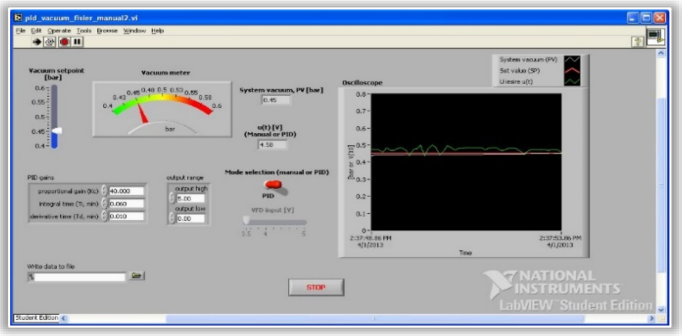


Figure 6 - Control panel of the virtual instrument

The Ziegler-Nichols tuning rules for the frequency response method were used; the disturbance was induced by changing the set point: one teatcup was opened by extracting the artificial teat, and then closed by inserting the teat back into the liner. These tests were performed at a vacuum level of 0.4 bar (40 kPa).

In order to evaluate vacuum stability the characteristics of the pulsation cycle (pulsation rate and ratio, duration of the pulsation phases, as defined by the ISO 3918:2007 standard) were evaluated with respect to the requirements of the ISO 5707 standard. The experiments performed for three vacuum levels: 0.35 bar, 0.40 bar and 0.45 bar (35, 40 and 45 kPa), in dry tests. Three tests were performed for each vacuum level and vacuum regulation method; the mean, standard error and standard error of the mean were calculated.

The values of the constants K_P, K_I and K_D were the ones established in the first phase of the tests.

A statistical analysis was performed in order to decide whether there was a significant difference between the permanent vacuum levels recorded for two regulation methods. The analysis was performed by the means of the Student's t-test for the level of significance.

RESULTS

In order to tune the PID controller using the Ziegler-Nichols tuning rules for the frequency response method, the integral time was set at 10000 and the derivative time was set to 0. The proportional gain was adjusted until the oscillations were sustained and had a constant amplitude, as displayed on the oscilloscope window of the control panel and thus the critical gain was obtained. The critical period T_c was measured using the recorded values of the vacuum signal.

The PID gains were then calculated using the formulae presented in table 1 (Aström and Murray, 2008), using the critical gain K_c and critical period T_c.

Table 1. Controller parameters for the Ziegler-Nichols frequency response method

Controller type	K_P	T_i	T_d
P	$0.5 \cdot K_c$	-	-
PI	$0.4 \cdot K_c$	$0.8 \cdot T_c$	-
PID	$0.6 \cdot K_c$	$0.5 \cdot T_c$	$0.125 \cdot T_c$

For the tested milking system, the critical gain was $K_c = 68$ and the critical period was $T_c = 7.53 \pm 0.46$ s. The calculated operating parameters of the PID controller were as follows: $K_P = 40$, $T_i = 4.76$ s (0.062 min), $T_d = 0.941$ s (0.015 min).

The results referring to the operating parameters of the system and vacuum stability are presented in tables 2 and 3.

Table 2. Operating parameters of the milking system

Regulation method	Item	Vacuum level [kPa] 35	40	45
Vacuum regulator	Pulsation rate [cycles/min]	48.4 ±0.231	51.9 ±0.266	55.9 ±0.200
	Pulsation ratio [%]	55.1/44.9	53.7/46.3	53.3/46.7
	Duration of b phase* [%]	44.9 ±0.137	41.21 ±0.362	39.74 ±0.270
	Duration of d phase** [s]	0.42 ±0.005	0.387 ±0.003	0.343 ±0.003
PID controller	Pulsation rate [cycles/min]	48.9 ±0.352	52.2 ±0.500	56.4 ±0.167
	Pulsation ratio [%]	54.6/45.4	53.8/46.2	53.2/46.8
	Duration of b phase [%]	44.02 ±0.352	41.98 ±0.405	39.40 ±0.113
	Duration of d phase [s]	0.42 ±0.006	0.387 ±0.012	0.337 ±0.003

Notes: *at least 30%[9]; **at least 0.15 s [7].

Table 3. Results regarding vacuum stability

Regulation method	Item	Vacuum level (SP) [kPa] 35	40	45
Vacuum regulator	mean vacuum level, $\bar{x}$* [kPa]	34.417	39.462	44.398
	standard deviation, S [kPa]	0.2020	0.230	0.226
	standard error of the mean, $S_{\bar{x}}$** [kPa]	0.0142	0.0162	0.0159
PID controller	mean vacuum level, $\bar{x}$ [kPa]	34.514	39.381	44.573
	standard deviation, S* [kPa]	0.172	0.195	0.186
	standard error of the mean, $S_{\bar{x}}$** [kPa]	0.0121	0.0138	0.0131
t-test	t_{calc}	5.174**	3.777*	8.480**
	$t_{0.05} = 3.539$; $t_{0.01} = 3.970$			

Notes: * for 200 recorded values;

** $S_{\bar{x}} = S / \sqrt{n}$;

*-significant difference; **-distinctly significant difference

The results presented in table 2 show that the opearting parameters of the system were not affected by the method used for vacuum regulation: there were no significant differences between the parameters taken into account (pulsation rate and ratio, duration of the phases) and the requirements of the ISO 5707:2007 standard were respected (see the corresponding notes).

The results presented in table 3 show that the use of the PID controller method for vacuum regulation led to lower standard errors than the ones achieved when a classical vacuum regulator was used. This means that lower vacuum fluctuations were recorded when the VFD controller method was used for vacuum regulation instead of the classic method (with mechanical vacuum regulator).

The statistical analysis of the results confirmed that there was a significant difference ($P<0.05$) between the tested variants (vacuum regulator and PID controller) for the 40 kPa vacuum level and distinctly significant differences ($P<0.01$) for the 35 and 50 kPa vacuum levels.

CONCLUSIONS

A variable frequency driver, controlled by the means of PID regulator, was developed in order to achieve vacuum regulation in a mechanical bucket milking machine. The PID regulator was implemented using the NI LabView capabilities.

Preliminary tests were performed over the milking system in order to adjust the values of the K_P, K_I and K_D constants of the PID controller, aiming to obtain a short rise time, a small overshoot and a small steady state error between the actual value of permanent vacuum and the desired one.

Another series of comparative tests aimed to evaluate the working parameters of the milking system (pulsation rate and ratio, duration of the pulsation phases) and vacuum stability, for different vacuum levels. The tests showed that vacuum regulation by the means of the PID controller did not adversely affect the working parameters of the system, while achieving better results regarding the stability of the permanent vacuum.

Note:
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