PRELIMINARY RESEARCHES REGARDING THE USE OF A VFD CONTROLLER FOR THE VACUUM PUMP OF THE MECHANICAL MILKING MACHINE

R. Roşca[1*], P. Cârlescu[1], I. Țenu[1], C-tin Chirilă[1]

[1]*University of Agricultural Sciences and Veterinary Medicine Iasi, Romania*

Abstract

To maintain the stable vacuum needed for milking cows, air must be removed from the system at the same rate at which air enters the system through the pulsators, claws, leaks, unit fall-off and other equipment such as milk meters when present. Conventional vacuum control is accomplished by using a vacuum pump, sized for the maximum air flow into the milking system, running a full speed. The difference between the pump capacity and the actual air entering the system is made up by allowing air to enter the system through a regulator. In this paper a variable frequency driver (VFD) is used in order to drive the vacuum pump at a controlled speed, so that the air removed equals the air entering the milking system; in this case no conventional controller or regulator is needed during milking This technology for controlling vacuum in a milking system allows a dramatic reduction in energy use, while still producing equivalent vacuum stability. 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. The preliminary tests proved that the used of the VFD controller led to a higher vacuum stability in terms of the error between the set vacuum value and the achieved values. The statistical analysis of the experimental results showed that there is a significant difference between the experimental results obtained for the two methods of vacuum regulation (with vacuum regulator and VFD controller).

Key words: variable frequency drive, milking equipment, vacuum stability

INTRODUCTION

The vacuum level and stability have a major effect over the mechanical milking process. According to Bade, Reinemann, Zucali, Ruegg and Thompson [1], the vacuum level and the compressive load applied to the teat when the liner collapses are the factors affecting the peak milk flow rate. Cows have a biological limit for a positive reaction to vacuum and exceeding these limits 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 [2]. Vacuum fluctuations generated within the milking cluster may lead to direct bacterial penetration, thus causing mastitis [2].

A typical mechanical milking system [6] contains a vacuum pump (2, fig. 1), driven by an electric motor (1); the vacuum pump creates vacuum into the vacuum pipeline (7), which is used for both the milk extraction and the pulsation of the liner. The vacuum level is regulated by the means of the vacuum regulator (4), placed downstream of the receiver. The vacuum pump is permanently operated at full capacity, providing a flow of air greater than the one entering the system through pulsators, claws, leaks. The difference between the air extracted by the pump and the necessary flow of air during milk extraction is compensated by the vacuum regulator, which allows supplementary air to enter into the system.

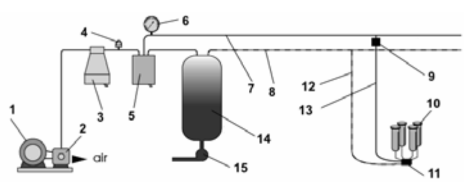

Fig. 1 Layout of a mechanical milking system
1-electric motor; 2-vacuum pump; 3-interceptor; 4-vacuum regulator; 5-sanitary trap; 6-vacuum gauge; 7-permanent vacuum pipeline; 8-milk pipeline; 9-pulsator; 10-teatcup; 11-claw; 12-long milk tube; 13-long pulse tube; 14-receiver; 15-milk pump.

*Corresponding author: rrosca@uaiasi.ro
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Figure 2 presents the basic construction of a vacuum regulator; it can be seen that, when the force due to the system vacuum acting upon the valve (2) exceeds its weight the inlet orifice (3) is opened and supplementary air enters the system, thus diminishing the vacuum level. The present-day milking systems use more sophisticated servo-operated regulators, equipped with mechanical amplification devices in order to improve the sensitivity and response rate of the regulator; the vacuum sensing point is located upstream from the air admission point [4].

In order to make the vacuum pump draw only the amount of air needed to compensate the air entering the system the speed of the pump should be variable (air flow depends on the pump speed). Thus the air removed by the pump equals the air entering the milking system; in this case the vacuum pump motor is controlled by the means of a variable frequency driver (VFD) and no conventional regulator is needed to maintain the imposed vacuum during milking. Figure 3 presents the schematics of milking system in which the variation of the pump speed allows the adjustment of the vacuum level.

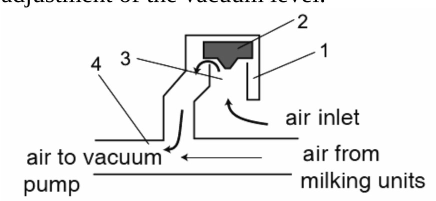

Fig. 2 Basic construction of a vacuum regulator [4]
1-body; 2-valve; 3-air inlet orifice; 4-vacuum pipeline.

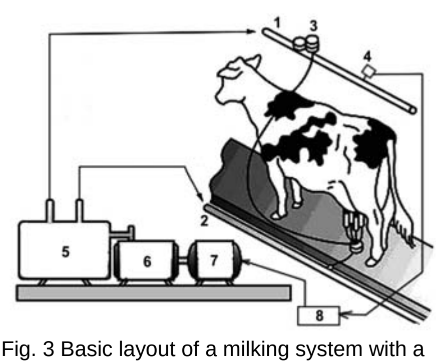

Fig. 3 Basic layout of a milking system with a VFD controlled vacuum pump
1-permanent vacuum pipeline; 2-milk pipeline; 3-pulsator; 4-pressure sensor; 5-receiver; 6-vacuum pump; 7-electric motor; 8-VFD.

The VFD (8) senses the vacuum level in the permanent vacuum pipeline (1) and adjusts the speed of the electric motor (7) in order to keep the vacuum level constant. This solution leads to a significant reduction in power consumption; in a study conducted by Pazzona et al. [3] energy savings between 24 and 87% were reported. In the same paper the results of the falloff tests showed no significant differences between the systems controlled by conventional regulators and the ones controlled through the variation of the vacuum pump speed. If the VFD controller is adjusted properly it can meet or even exceed the vacuum stability recorded by the systems equipped with conventional regulators [3, 4], the target being a receiver vacuum within ±2 kPa of the vacuum set point during normal milking [8].

In this paper a variable frequency driver (VFD) was used in order to drive the vacuum pump of a bucket milking machine at a controlled speed. The VFD was controlled by a computer; a virtual instrument (vi) was used to emulate a PID (Proportional-Integral-Derivative) regulator. 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 the response time of the system with the vacuum pump running at a variable speed.

MATERIAL AND METHOD

A bucket milking machine was used in this study; fig. 4 presents the schematics of the milking machine. The machine was equipped with a BRK pneumatic type pulsator and four Boumatic R-1CX type teatcups. Artificial teats, manufactured according to the ISO 6690:2007 standard, were inserted into the teatcups. In order to establish the working parameters of the milking process (pulsation rate and ratio), the milking system was equipped with two Smartec SPD015Aasil absolute pressure sensors [10] (not shown on the diagram), mounted on the short vacuum and milk tubes connecting one of the teatcups to the claw. The pulsation ratio was defined according to the specifications of the ISO 5707:2007 [7] standard.

The schematic of the system controlling the speed of the electric motor driving the vacuum pump is presented in Figure 5. During the tests another Smartec

SPD015AAsil absolute pressure sensor was used to monitor the vacuum in the permanent vacuum line, in order to provide the signal for the VFD controller.

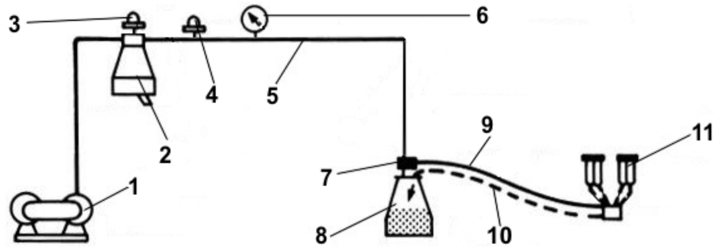

Fig. 4 Schematics of the milking machine
1-vacuum pump; 2-interceptor; 3-vacuum regulator; 4-pressure sensor; 5-vacuum line; 6-vacuum gauge; 7-pulsator; 8-bucket; 9-long vacuum line; 10-long milk line; 11-milking unit

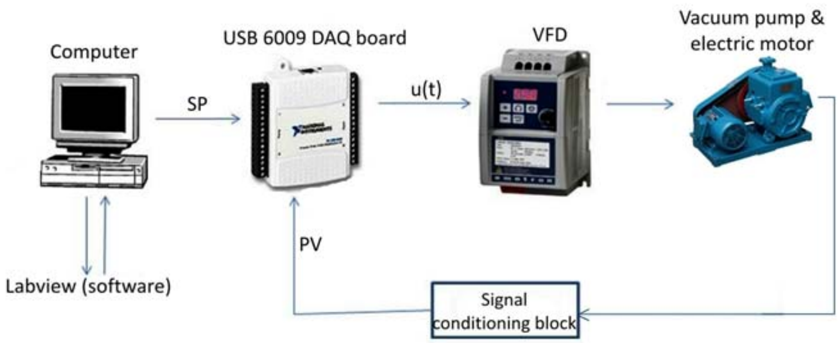

Fig. 5 The PID regulation loop

The electric signal from the pressure sensor (4, Figure 4) was fed to the data acquisition (DAQ) board. Based on the software running on the computer the entire system (DAQ board, VFD controller and computer) acts 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 vacuum pipeline. The controller calculates the output signal u(t), which is then used to command the VFD and adjust the running speed of the electric motor and vacuum pump.

The PID controller output signal is given by the relation:

$$u(t) = K_p \cdot e(t) + K_I \cdot \int e(t) \cdot dt + K_D \cdot \frac{de(t)}{dt},$$

where the error signal is e(t) = SP-PV; K_P, K_I and K_D are the proportional, integral and derivative gains, respectively.

A virtual instrument was created using the National Instruments LabView 7.1 in order to control the speed of the electric motor driving the vacuum pump; the PID regulator implemented within the virtual instrument uses the “Simple PID Demo” virtual instrument created by National Instruments [9]. The software allowed the adjustment of the set point (desired vacuum level) and of the proportional, integral and derivative gains; the SP and PV values were recorded on disc for subsequent analysis regarding vacuum stability. Fig. 6 presents the control panel of the virtual instrument.

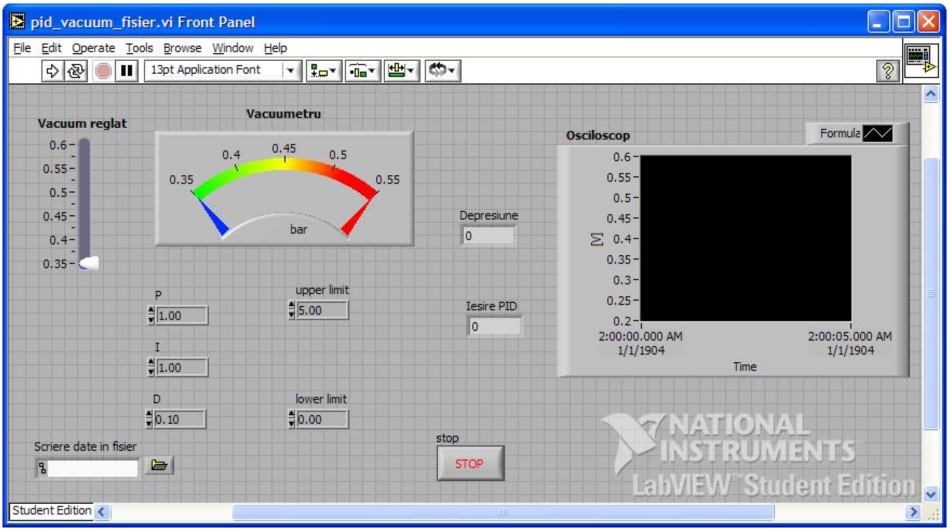

Fig. 6 The control panel of the virtual instrument

The milking system was tested in two phases: the first phase aimed to tune the values of the K_P, K_I and K_D constants, while the purpose of the second one was to compare the two methods of vacuum regulation (classic regulator and adjustment of the pump speed).

For the first phase fall-off tests were performed, during which one teatcup was opened by extracting the artificial teat, and then closed by inserting the teat back into the liner.

The parameters K_P, K_I and K_D were modified with respect to the vacuum undershoot, overshoot and rise time (fig. 7), taking into account the requirements of the ISO 6690:2007 standard [8]. These tests were performed at a vacuum level of 0.4 bar (40 kPa).

For the second series of tests the permanent vacuum values were recorded and compared in terms of vacuum stability, using the average value of the vacuum, the standard deviation and the standard error of the mean. Three vacuum levels were considered: 0.35 bar, 0.40 bar and 0.45 bar (35, 40 and 45 kPa).

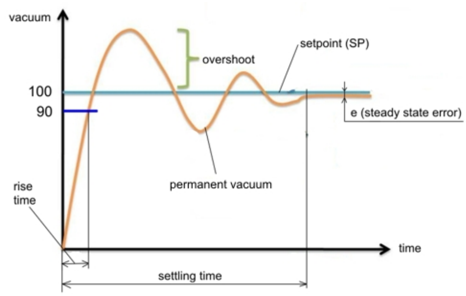

Fig. 7 Response of a typical PID closed loop system

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

The characteristics of the pulsation cycle (pulsation rate and ratio, duration of the pulsation phases, as defined by the ISO 3918:2007 standard) [6] were evaluated with respect to the requirements of the ISO 5707 standard [7] and compared.

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 AND DISCUSSIONS

Tuning of the PID controller

For the first tests the values of the constants were chosen as follows: $K_P = 5$, $K_I = 0$ and $K_D = 0.1$. The results of the fall-off test are presented in fig. 8; the chart shows that the rise time (the time required for the permanent vacuum to reach 90% of the set value of 0.4 bar after closing the teatcup) was high (15 s), while the overshoot was comprised between 0.015 and 0.02 bar.

The decrease of the rise time may be achieved by increasing the integral gain [5]; consequently, for the next tests, the integral gain was set to 1. Figure 9 shows a significant reduction of the rise time (2 s); as expected, the steady state error was lower in comparison with the previous situation. On the other side, the system overshoot recorded high values (0.07 bar, 0.7 kPa), leading to the conclusion that a lower value of the integral gain should be considered in order to reduce the overshoot [5]. The results presented in Figure 10 were obtained with an integral gain $K_I = 0.2$; the overshoot was significantly reduced, but again the rise time was too high (20 s).

In order to reduce the rising time the proportional and derivative gain were increased and the integral gain was further decreased; finally, the following values were used: $K_p = 20$, $K_I = 0.05$, $K_D = 0.5$. The chart presented in fig. 11 shows that the overshoot did not exceed 0.03 bar (0.3 kPa), the rise time was 5 s, and the steady state error was not significant. Taking into account that the ISO 6690 standard imposes a maximum value of the overshoot of 2 kPa, these settings were used for the second phase of the tests.

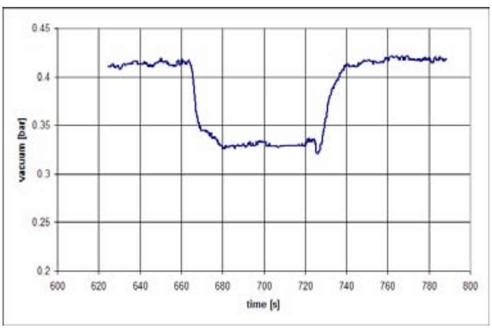

Fig. 8 Vacuum trace for $K_p = 5$, $K_I = 0$, $K_D = 0.1$

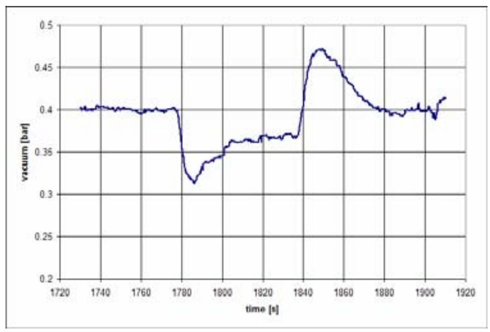

Fig. 9 Vacuum trace $K_p = 5$, $K_I = 1$, $K_D = 0.1$

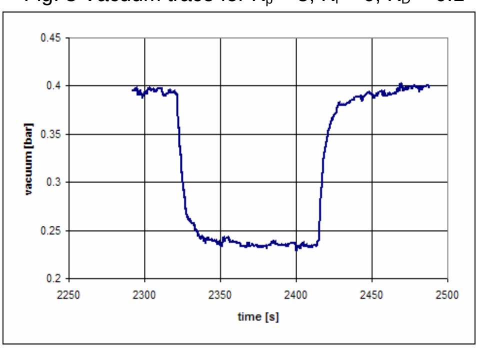

Fig. 10 Vacuum trace for $K_p = 5$, $K_I = 0.2$, $K_D = 0.1$

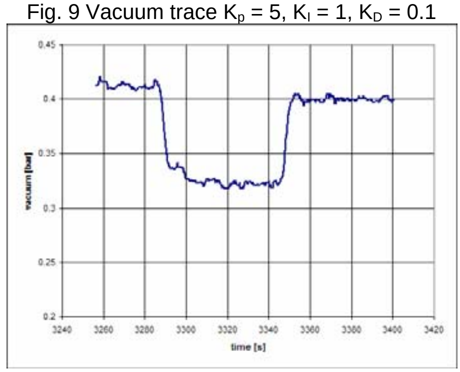

Fig. 11 Vacuum trace for $K_p = 20$, $K_I = 0.05$, $K_D = 0.5$

Evaluation of the working parameters and vacuum stability

The results referring to the working parameters of the system and vacuum stability are shown in Tables 1 and 2.

The results presented in Table 1 show that the working 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 2 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 (the two sets of vacuum values) for the 40 kPa vacuum level and a distinctly significant difference (P<0.01) for the 35 and 50 kPa vacuum levels.

Table 1 Working 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 2 Results regarding vacuum stability

Regulation method	Item	Vacuum level (SP) [kPa]		
		35	40	45
Vacuum regulator	mean vacuum level, $\overline{X}$* [kPa]	34.417	39.462	44.398
	standard deviation, S [kPa]	0.2020	0.230	0.226
	standard error of the mean, $S_{\overline{x}}$** [kPa]	0.0142	0.0162	0.0159
PID controller	mean vacuum level, $\overline{X}$ [kPa]	34.514	39.381	44.573
	standard deviation, S* [kPa]	0.172	0.195	0.186
	standard error of the mean, $S_{\overline{x}}$** [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; ** $S_{\overline{x}} = S / \sqrt{n}$; *-significant difference; **-distinctly significant difference

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.

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