UKRAINIAN JOURNAL OF MECHANICAL ENGINEERING AND MATERIALS SCIENCE
Vol. 7, No. 3-4, 2021

Petro Yatsunskyi

Department of Equipment Design and Operation, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, Ukraine, e-mail: petro.p.yatsunskyi@lpnu.ua, ORCID 0000-0002-1609-7009

THE PRESSURE OSCILLATION IN THE INTER-WALL CHAMBER OF THE TEAT CUP

Received: June 28, 2021 / Revised: August 30, 2021 / Accepted: December 28, 2021

https://doi.org/10.23939/ujmems2021.03-04.011

Abstract. Factors influencing the vacuum gauge pressure in the inter-wall chamber of milking teat cups of a milking machine with a pneumo- and electromagnetic pulse generator with a combined collector are analyzed. The main factors of research and the limits of their variation are formed, the matrix of multifactor planned experiment is developed, and also results of experimental researches are received. According to the results of experimental studies, the regression equations in coded and real or natural values are derived, which characterize the dependence of pressure oscillation in the inter-wall chamber of milking teat cups on the pulsation frequency, milk ejection intensity and the ratio between strokes. A graphical model of interpretation of regression dependence based on experimental data is built. Student's t-test, Fisher's and Cochran’s criteria are calculated, which show the adequacy and reproducibility of the obtained model of the technological process using of the experimental pulse generator with combined collector of the milking machine.

Keywords: pneumo- and electromagnetic pulsator, inter-wall chamber, vacuum, pulsation frequency, regression model

Introduction and Problem Statement

Today, the adaptive milking is dominant in dairy farming; adaptive milking process is evaluated by a large number of mutually agreed parameters that affect the indices of control or measurement and characterize the optimality of the system [7, 8]. Milking equipment with automatic control is favourable for the cow [24]. Also, the components of the robotic adaptive milking machine must meet the requirements [18, 19]. To bring the milking conditions to the individual characteristics of the cow, the best solution is to automatically adjust the vacuum for each teat [6]. The pulsator is the main executive unit in this case.

Vacuum and pulsation frequency affect the adaptation of the milking system to the cow, also vacuum and pulsation or ripple frequency determine the softness and velocity of milking [27]. The duration of milking is reduced by 25 % with changes in the ratio between strokes from 50:50 to 70:30, a constant pulsation frequency of 1 Hz and vacuum in the system of 42 kPa; under the 51 kPa vacuum in system, the duration of milking is reduced by only 5 % [32]. The pulsation coefficient of the milking machine affects the time of milk flow, milking time and the state of sucking [15]. Researchers [21] stated that the ripple frequency, the ratio between the strokes and vacuum level effect on the milk ejection dominantly.

Vacuum gage pressure is an important factor that affects the intensity of milk production in the system of “machine-cow” [9, 10]. The stability of the vacuum gage pressure was investigated depending on the method of regulation i.e. in the vacuum line or directly in the milking machine [26]. Also, the authors [29] studied the oscillations of vacuum gage pressure depending on: a) the configuration of the vacuum and milk systems (length of pipelines, their diameter and other parameters that have influence on the pressure loss); b) the flow rate of milk in the milk line; c) the velocity of air movement in the vacuum line. They found that with decreasing of milk intensity, the vacuum gage pressure increases both in the vacuum and milk line, and in the under teat area of the milking cupsas well. Therefore, the studies of vacuum oscillations in the milking machine are important for the technological and technical parameters of the milking [2]. Vacuum oscillations in the milking machine reduce the efficiency of milking and are factors that affect the disease of the udder in cows during mechanical milking. These parameters create reverse flows of air-milk mixture, which can reach significant speeds with the appropriate design solutions of the milking machine [1, 17, 22, 25].

The vacuum instability during milking and the frequency of vacuum pulsations from the operation of the pulsator together with the high vacuum at the end of the cow udder teat increase the likelihood of teat disease and reduce the intensity of milk ejection [4]. Significantly high value of vacuum at the end of the teat reduces the peak intensity of milk production, as well as swelling of the teat [16]. If the vacuum is very high, the milking teat cups rise more intensely on the teats, which can lead to teat injuries and contamination of the teat tips. Therefore, a number of authors investigated the influence of the intensity of milk ejection in the milking machine on the vacuum, the nature of the graphic curves of change of increase and decrease of vacuum at given frequencies of the pulsator operation [3, 5, 13, 14, 23, 28, 30, 33].

The results of the study of the change in vacuum in the elements of the milking machine were analyzed using different methods and models, linear regression [20, 31], nonlinear regression [25] or quadratic dependences.Analytical models describing the nature of pressure losses [10, 11] and experimental research methods were used to model the characteristics of the vacuum [12].

The analysis of researches shows that the substantiation of the pneumatic and electromagnetic pulse collector parameters which influence technological process of milk ejection is of current importancefor increase of efficiency of the automated milking of cows. Therefore, the study of pressure oscillations in the inter-wall chamber of milking teat cups of a milking machine with a pneumatic and electromagnetic pulse collector is anissue of the day.

Main Material Presentation

The aim of this work was to investigate the pressure oscillation in the inter-wall chamber of the milking cup of the milking machine with a combined pneumo- and electromagnetic pulse collector depending on the parameters of the technological process of machine milking of cows.

The processes were investigated by a factor-planned experiment. The method of the [9] experiment is taken as a basis, with regard to the weight of each factor and decoding the members of the regression dependence into the coefficients of the equation for the natural or real values of the factors. The response criterion was the *Pu* [kPa] vacuum pressure in the inter-wall chamber of the milking teat cup, the factors were the pulsation frequency of *n* [Hz] – x_1, milk ejection intensity of *q* [g/sec] -x_2 and the ratio between cycles of *t/T* - x_3. The values of the *n* pulsation frequency were taken at the levels of 0.67, 1.0 and 1.33 [Hz], milk ejection intensity of *q* was 33.0, 39.0 and 45.0 [g/sec] and the ratio between cycles was 0.67, 1.5 and 2.33.

The coding factors, according to the theory of experiment planning, are given in Table 1.

To study the influence of these factors according to the matrix of the experiment (Table 2), the experiment was repeated three times according to the previously described method [10]

Table 1

Levels of variation of factors and their code values in the planned experiment

Factors	Designation	Dimension	Levels of factors			Variation interval
			upper	null	lower	
			Code values			
			+ 1	0	- 1	
Pulsation frequency, *n*	x_1	[Hz]	1.33	1.0	0.67	0.33
Milkejectionintensity, *q*	X_2	[g/sec]	45.0	39.0	33.0	6.0
Proportionbetweenthestrokes, *t/T*	X_3		70:30 = 2.333	60:40 = 1.5	40:60 = 0.667	0.833

In order for the planning matrix to have the property of orthogonality, we enter a column in Table 2 with adjusted values of the level $x^{/}$, which is calculated by the formula:

$$\left(x_i^{/}\right)^2 = x_i^2 - \frac{\sum x_i^2}{N}. \qquad (1)$$

The matrix of calculations of the coefficients of the equation is given in Tabl. 2, in which 2-11 columns form an orthogonal scheduling matrix; 12[th] column is the response value of the experiment.

Table 2

Extended matrix of orthogonal planning of the experiment for a three-factor model of the second order of dependence of vacuum pressure in the inter-wall chamber of the milking teat cup on factors

№ experiment	x_1	x_2	x_3	$x_1 \cdot x_2$	$x_1 \cdot x_3$	$x_2 \cdot x_3$	$\left(x_1^{/}\right)^2$	$\left(x_2^{/}\right)^2$	$\left(x_3^{/}\right)^2$	$x_1 \cdot x_2 \cdot x_3$	*y* (*Pu*), [kPa]
1	2	3	4	5	6	7	8	9	10	11	12
1	+1	+1	+1	+1	+1	+1	0.3333	0.3333	0.3333	+1	14.75
2	0	+1	+1	0	0	+1	-0.6667	0.3333	0.3333	0	15.73
3	-1	+1	+1	-1	-1	+1	0.3333	0.3333	0.3333	-1	18.24
4	+1	+1	-1	+1	-1	-1	0.3333	0.3333	0.3333	-1	20.87
5	0	+1	-1	0	0	-1	-0.6667	0.3333	0.3333	0	24.56
6	-1	+1	-1	-1	+1	-1	0.3333	0.3333	0.3333	+1	26.61
7	+1	+1	0	+1	0	0	0.3333	0.3333	-0.6667	0	17.73
8	0	+1	0	0	0	0	-0.6667	0.3333	-0.6667	0	19.54
9	-1	+1	0	-1	0	0	0.3333	0.3333	-0.6667	0	25.65
10	+1	-1	+1	-1	+1	-1	0.3333	0.3333	0.3333	-1	17.08
11	0	-1	+1	0	0	-1	-0.6667	0.3333	0.3333	0	22.41
12	-1	-1	+1	+1	-1	-1	0.3333	0.3333	0.3333	+1	23.12
13	+1	-1	-1	-1	-1	+1	0.3333	0.3333	0.3333	+1	23.78
14	0	-1	-1	0	0	+1	-0.6667	0.3333	0.3333	0	28.02
15	-1	-1	-1	+1	+1	+1	0.3333	0.3333	0.3333	-1	28.56
16	+1	-1	0	-1	0	0	0.3333	0.3333	-0.6667	0	20.35
17	0	-1	0	0	0	0	-0.6667	0.3333	-0.6667	0	24.90
18	-1	-1	0	+1	0	0	0.3333	0.3333	-0.6667	0	29.33
19	+1	0	+1	0	+1	0	0.3333	-0.6667	0.3333	0	16.30
20	0	0	+1	0	0	0	-0.6667	-0.6667	0.3333	0	16.60
21	-1	0	+1	0	-1	0	0.3333	-0.6667	0.3333	0	20.10
22	+1	0	-1	0	-1	0	0.3333	-0.6667	0.3333	0	22.15
23	0	0	-1	0	0	0	-0.6667	-0.6667	0.3333	0	25.04
24	-1	0	-1	0	+1	0	0.3333	-0.6667	0.3333	0	26.98
25	+1	0	0	0	0	0	0.3333	-0.6667	-0.6667	0	19.92
26	0	0	0	0	0	0	-0.6667	-0.6667	-0.6667	0	20.70
27	-1	0	0	0	0	0	0.3333	-0.6667	-0.6667	0	27.97
∑	18	18	18	12	12	12	-	-	-	8	-

The studies were performed on a stand (laboratory hardware) for experimental researches of milking equipment (Fig. 1**)** [8]. The values of vacuum gage pressure were measured by intelligent pressure sensors, which are installed in the sub-wall and inter-wall chambers of the milking teat cup, in the collector and in the milk hose. The digital code from the sensors was read by the central computer via the data reception interface.

Fig. 1. General view of the experimental laboratory stand of ACPS
1 – the reservoir of the milk simulator; 2 – the simulator of milk ejection intensity; 3 – teat cups;
4 – sensors of the pressure in the inter- wall and under teat area of the teat cups; 5 – sensor of the pressure in the milk hose; 6 – measuring device; 7 – the electronic module of milk ejection gauge; 8 – DAC-ADC;
9 – the control system (main computer); 10 – the system of data processing of the pressure sensors;
11 – the electronic module of visualization of data-measuring parameters; 12 – blocks of regulated voltage;
13 – the pneumo-electromagnetic pulsator; 14 – the milk tap; 15 – the vacuum hose; 16 – the imitation of udder;
17 – the collector; 18 – the milk hose

According to Table 2 we calculate the coefficients of the regression equation. The values of the regression coefficients characterize the contribution of each factor in the value of the response function and are calculated by the formulas:

$$b_1 = \frac{\sum(x_1 \cdot y)}{18}, b_2 = \frac{\sum(x_2 \cdot y)}{18}, b_3 = \frac{\sum(x_3 \cdot y)}{18}\ b_{11} = \frac{\sum((x_1^{/})^2 \cdot y)}{6},$$
$$b_{22} = \frac{\sum((x_2^{/})^2 \cdot y)}{6}, b_{33} = \frac{\sum((x_3^{/})^2 \cdot y)}{6}, b_{12} = \frac{\sum(x_1 \cdot x_2 \cdot y)}{12},\ b_{13} = \frac{\sum(x_1 \cdot x_3 \cdot y)}{12}, \quad (2)$$
$$b_{23} = \frac{\sum(x_2 \cdot x_3 \cdot y)}{12},\ b_{123} = \frac{\sum(x_1 \cdot x_2 \cdot x_3 \cdot y)}{8},$$
$$b_0 = \frac{\sum y}{27} - 0.67 \cdot b_{11} - 0.67 \cdot b_{22} - 0.67 \cdot b_{33}$$

The results of the calculation of the coefficients of the regression equation are given in Table 3.

For use in the regression equation of natural values of factors, we convert the linear terms of the equation from coded values to natural or real by the formula:

$$b_i x_i = \frac{b_i}{\varepsilon_i} X_i - \frac{b_i}{\varepsilon_i} X_{0i}, \quad (3)$$

where X_i – the natural or real value of the factor; X_{i0} – the natural value of the factor at zero level; ε – the variation interval.

The linear members of the interacting equation were transformed by the formula:

$$b_{ij}x_i x_j = \frac{b_{ij}}{\varepsilon_i \varepsilon_j}\left(X_i X_j - X_i X_{0j} - X_j X_{0i} + X_{0i} X_{0j}\right). \quad (4)$$

The square members or terms of the equation were transformed by the formula:

$$b_{ii}x_i^2 = \frac{b_{ii}}{\varepsilon_i^2}\left(X_i^2 - 2X_i X_{0i} + X_{0i} X_{0i}^2\right). \quad (5)$$

The results of natural coefficients calculation of the regression equation are given in Table 3.

Results and Discussion

According to the method of [10] the real values of the regression equation were calculated, which are given in Table 3.

Table 3

The calculations results of the regression equation coefficients of the dependence of pressure fluctuations in the inter-wall chamber of the milking teat cup on the factors

Coefficient of the regression equation	Coded coefficient	Real coefficient
b0	22.37383	55.193213
b1	-2.97833	-3.113375
b2	-1.88167	-1.054413
b3	-3.45667	14.355110
b12	0.220556	-0.287718
b13	0.168611	-9.738675
b23	-0.46306	-0.358321
b11	0.249074	2.242115
b22	0.539074	0.014974
b33	-1.1837	-1.718252
b123	0.440417	0.265338

The regression equation that models the change in the vacuum pressure in real coefficients will look like:

$$P_u = 55{,}193217 - 3{,}113375\cdot n - 1{,}054413\cdot q + 14{,}355110\cdot\left(\frac{t}{T}\right) - 0{,}287718\cdot n\cdot q -$$
$$-9{,}738675\cdot n\cdot\left(\frac{t}{T}\right) - 0{,}358321\cdot q\cdot\left(\frac{t}{T}\right) + 2{,}242115\cdot n^2 + 0{,}014974\cdot q^2 - \quad , \quad (6)$$
$$1{,}718252\left(\frac{t}{T}\right)^2 + 0{,}265338\cdot n\cdot\left(\frac{t}{T}\right)\cdot q$$

where *Pu*– vacuum pressure in the inter-wall chamber of teat cups, [kPa]; *n* – the ripple frequency, [Hz]; *q* – the milk ejection, [g/sec]; *t/T* – the ratio between the strokes

This equation of the dependence of the vacuum pressure on the factors is presented graphically in Fig. 2. The Fig. 3 shoves a contour graph which is for more detailed information.

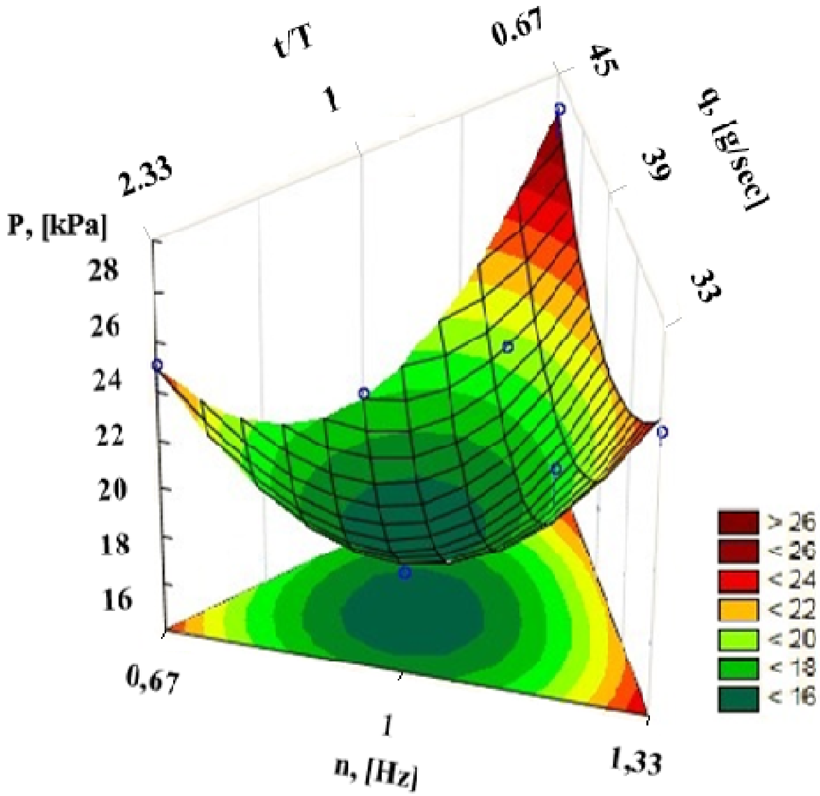

Fig. 2. Dependence of vacuum gauge pressure in the inter-wall chamber of the milking teat cup on the parameters of the technological process
n – the ripple frequency, [Hz]; q – the milk ejection, [g/sec]; t/T – the ratio between the strokes

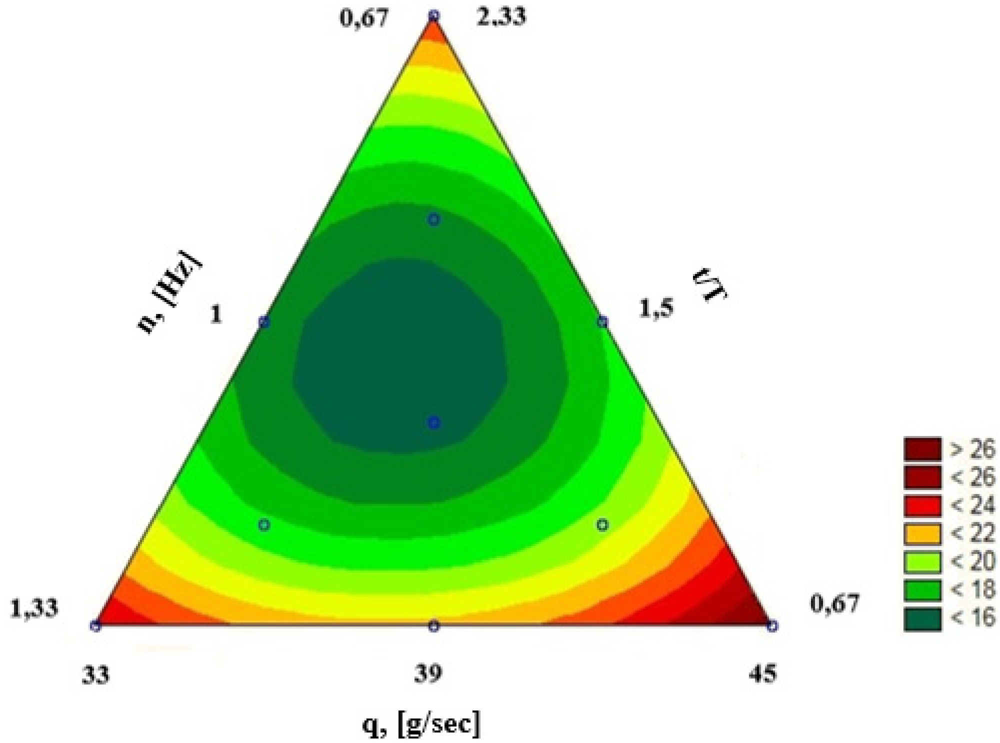

Fig. 3. Contourplot –isolinesof the response criterion
n – the ripple frequency, [Hz]; q – the milk ejection, [g/sec]; t/T – the ratio between the strokes

The results of the analysis of experimental data on the reproducibility of experiments by Cochran's test, on the significance of the coefficients of regression equations by Student's *t*-test and the assessment of the adequacy of models by Fisher's *F*-test showed the following.

The calculated value of the Cochran test is 0.220, which is less than the tabular value, which is 0.234 and confirms the reproducibility of the experiments according to the dependence (6).

The average value of the variance is S^2 = 3.447. To compare each regression coefficient with the expression of $S_A \cdot t$we determined the Student's *t*-test for a significance level of 0.95. Accordingly, the tabular value of the *t*-test is t = 2.004.

The values of the $S_A^2 \cdot t$ = 0.085expression were compared with the coefficients of (6) equation. The condition of $|b_i| > S_A^2 \cdot t$ is fulfilled beside of the b_{23} and b_{33} coefficients, accordingly, we can conclude that the other coefficients of (6) equation are significant.

To test the suitability of the (6) regression equation for a characteristic description of the dependence of the optimization criterion on the factors, we define the Fisher criterion (*F*-criterion).

The variance of adequacy of $S_{ад}^2$ and the calculated value of the *F*-criterion F_p are accordingly of $S_{ад}^2$ = 5.475 and F_p = 1.588.

For the calculated degrees of freedom of the main variance and the variance of adequacy, we take the tabular value of the *F*-criterion $F_т$ = 1.95.

The adequacy of the model is estimated under the $F_p \leq F_T$ condition, accordingly of $1.58 \leq 1.95$, so the model described by equation of (6) is adequate.

Conclusions

Depending on the intensity of milk ejection, pulsation frequency and the ratio between strokes, the regression model of pressure oscillation in the inter-wall chamber of milking teat cups of a milking machine with a combined pneumo- and electromagnetic pulse collector is nonlinear. Oscillations of vacuum gage pressure in the inter-wall chamber of milking teat cups of the milking machine increase with increasing of the milk ejection intensity, pulsation frequency and ratio between strokes which are different of the nominal. The maximum oscillation of the vacuum in the inter-wall chamber of milking teat cups is 28 [kPa] at a milk ejection intensity of 45 [g/sec], a pulsation frequency of 1 [Hz] and a ratio between suction and compression strokes of 0.67.

Vacuum oscillations in the inter-wall chamber of milking teat cups increasewith increasing of the pulsation frequency and decreasing of the suction stroke duration.

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