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Mathematical models for the prediction of vacuum dynamics of a milking system with four-way milking cluster

Dört yollu sağım başlığına sahip bir sağım sisteminin vakum dinamiklerinin tahminlemesine yönelik matematiksel modellerin geliştirilmesi

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ABSTRACT

Objective: The objective of this study was to determine the effects of system vacuum, pulsation rate and ratio and flow rate on vacuum dynamics of a milking system with four-way cluster. In order to meet this objective, empirical functions were developed to predict vacuum related dependent variables. These dependent variables were considered to be vacuum drops and fluctuations in b and d-phase and in claw along with average claw vacuum and teat end vacuum for four-way milking cluster.
Material and Methods: Experiments based on the central composite design, one of the designs in Response Surface Methodology (RSM), and using water and artificial teat were conducted in the laboratory. The data obtained from the experiments were then used to develop functions in polynomial form that allowed predicting the vacuum related variables.
Results: Eight different functions were developed. The coefficient of the determination (R^2) for all the models was above 0.9. It is believed that the models developed in this study can be used to design the milking system equipped with four-way milking cluster.
Conclusion: The simplest models are the ones that are developed for the average claw vacuum and the models developed for the vacuum drops in d-phase and claw. The common point of these three models along with the average vacuum prediction function is that there is no quadratic or cubic term entered into the model. The highest vacuum drops in b-phase for four-way milking cluster occurs when the pulsation ratio of 62:38. The system behavior for vacuum drops in d-phase is different than b-phase and a linear surface is valid. It only consists of flow rate and pulsation ratio.

Keywords: b and d-phase, machine milking, teat- end vacuum, vacuum drops, vacuum fluctuations

ÖZ

Amaç: Bu çalışmanın amacı sistem vakum, nabız oranı, nabız sayısı ve debinin (süt akış miktarı) dört yollu sağım başlığına sahip bir sistemde vakum dinamikleri üzerindeki etkilerini belirlemektir. Bu amaca ulaşma yolunda vakum ilintili değişkenler için ampirik modeller geliştirilmiştir. Dört yollu sağım başlığı için bağımlı değişkenler; vakum düşüşleri, pençede ve b - d fazında vakum dalgalanmaları yanısıra ortalama pençe vakumu ve meme ucu vakum değerleri olarak ele alınmıştır.
Materyal ve Yöntem: Tepki Yüzeyleri Metodolojisi (TYM) desenlerinden biri olan merkez esaslı deneme desenine uygun olarak laboratuvar koşullarında yapay meme ve su kullanılarak denemeler gerçekleştirilmiştir. Denemelerden elde edilen veriler kullanılarak vakum ilintili değişkenlerin tahminlenmesine yönelik polinomiyal formda tahminleme modelleri geliştirilmiştir.
Araştırma Bulguları: Çalışmada her birinin tahminleme kaysayısı (R^2) 0.9'un üzerinde olan sekiz farklı model geliştirilmiştir. Bu çalışmada geliştirilen modellerin dört yollu sağım başlığına sahip bir sağım sisteminin özellikle vakum düşüşleri ve dalgalanmaları açısından daha iyi performans sağlayıcı şekilde dizayn edilerek kullanılabileceğine inanılmaktadır.
Sonuç: Çalışmada geliştirilen en basit modeller ortalama pençe vakum modeli, d fazında ve pençede ve vakum düşüşleri modelleri olmuştur. Geliştirilen bu üç modelin ortak noktası ise çalışmada ele alınan hiç bir değişkenin kuadratik yada kübik formunun modeller içerisinde yer almamış olmasıydı. Dört yollu sağım başlığında en yüksek vakum düşüşü nabız oranının 62:38 olduğunda elde edilmiştir. Sistemin d fazındaki vakum düşüşleri b fazından farklı olup sadece nabız oranı ve debi değişkenlerinden oluşan basit bir formdadır.

Anahtar sözcükler: b ve d fazı, makinalı sağım, meme ucu vakumu, vakum düşüşleri, vakum dalgalanmaları

INTRODUCTION

In the last five years, a considerable progress through the development of quarter individual milking systems was achieved. Many of the recently developed technologies are marketed and purchasable now. But, not all of the new technologies have been tested for their proper functions and their ability to produce optimal vacuum conditions. The high importance of optimal vacuum application in milking systems and the necessity for the individual quarter treatment of each udder quarter in milking systems are relevant for each successful milking process.

Different kinds of vacuum changes at the teat can happen and these are considered to be vacuum drops, cyclic and irregular vacuum fluctuations and they have an impact on the performance of the milking system (Ambord and Bruckmaier, 2010). Many studies in the past were conducted and the different kinds of milking systems were evaluated based on vacuum drops and fluctuations.

The individual quarter technique can be used to minimize the milking time of all quarters by the help of early removal of fast milking quarters or through slow down these quarters, so that all quarters finish milking at the same time (Reinemann, 2010). However, published evidences have shown that the monitoring of mastitis indicators in the milk from individual quarters increases accuracy and reliability of interpretation (Berglund *et al*, 2007). Some other relevant sources show in the following, the importance of the vacuum conditions in milking systems for the success of the milking process. Many other studies indicated that high vacuum levels and vacuum fluctuations that occur during the milking phase had negative effects on teat conditions and udder health. On the other hand, fast removal of milk but eliminating the unwanted effects of machine milking on mechanical load on teat end is the primary objective.

Caria *et al.* (2011) studied the effects of vacuum level on machine milking on buffalo and compared the effects of milking at low vacuum (36 kPa) and medium vacuum (42 kPa) on milk emission characteristics and system performance. They have found that When using 36 kPa vacuum, a significant increase in milking time and in the lag time before milk ejection occurred, as well as a decrease in average flow rate and residual milk. However, the vacuum level did not influence both milk yield and milk ejection time.

Ströbel *et al.* (2013) conducted a study with such an assumption that in the future, the number of lesions, oedema and hyperkeratosis can be reduced through the application of a more appropriate teat-end vacuum and teat-end massage during milking. They developed a vacuum control system and the most important conclusion made was that the control system can be introduced to all kinds of individual quarter milking systems.

Bessier *et al.* (2016) stated that the most of the available scientific literature concerning claw vacuum drops and fluctuations (identical to teat-end vacuum) during machine milking has been published in the 1960s and 1970s and the studies conducted in this period were related to the efffects of pulsation and vacuum including the impacts of irregular and cyclic vacuum fluctuations on milking performance and udder health in dairy cows. Furthermore they implied that fewer studies have been carried out more recently on modern types of dairy cows, and milking machines, and have been evaluated with modern statistical methods and software. They also recommended that it is necessary to conduct new studies on the influence of vacuum drops and fluctuations, high vacuum levels and long milking durations on milking performance and udder health of dairy cows.

Based on the reviewed literature and theoretical background, a study on four-way milking cluster was conducted under the laboratory conditions. Hence, the objective of this study was to develop empirical functions in order to predict and evaluate the system performance. Four variables; system vacuum, pulsation ratio, flow rate and pulsation rate were considered. The effects of these variables on vacuum dynamics of the milking system with four-way milking cluster were evaluated. For the evaluation purposes, the polynomial functions were developed by using RSM.

MATERIAL and METHODS

Experiments using RSM and water were conducted in the lab and artificial teats were used during the wet-tests and vacuum measurements were made according to ISO 6690 (ISO, 2007a) as used for testing other type of milking systems (Öz and Bilgen, 2004). The data were recorded by the use of Milko Test MT52. The measuring accuracy and scan frequency of this device are $<$ 0.5 % and 1 kHz, respectively and it is specially designed for testing vacuum pumps, milking equipments, pulsators and vacuum behavior over the time. The four way milking cluster by GEA as depicted in Figure 1 allows a quarter individual extraction of the milk.

Figure 1. General view of the four -way milking cluster.

Şekil 1. *Dört yollu sağım başlığının genel görünümü.*

The four-way milking cluster works with four chamber principle (cluster-height 40 mm; total cluster-diameter 120 mm). It is separated into four chambers; each has a volume of 65 ml and transmits the milk separately.

The recommended claw vacuum by ISO 5707 (2007b) should remain within a range of 32–42 kPa during peak milk flow to ensure fast, complete and gentle milking. This range is considered to be appropriate in terms of adequate liner movement and sufficient pressure on the teat during d-phase. The pressure lower than 32 kPa may result in liner slip while the teat end vacuum higher than 42 kPa can cause teat tissue damage. For the milking system with four-way vacuum cluster, the vacuum switch-off application (kick-off-function) with four balls avoids an additional vacuum supply to the teat cup when the cluster was refused by the cow. Therefore, there is no suction of dirt and manure into the direction to the milk receiver.

In this study, RSM was used and laboratory experiments were carried out using four way milking cluster. Basically, RSM is an optimization technique and a mixture of mathematics and statistics. The brief information about this technique is given below. For further details, the readers are referred to read the textbook written by Box and Draper (1987).

The response surface problem usually centers on an interest in some response *Y*, which is a function of *k* independent variables $\xi_1, \xi_2, ..., \xi_k$, that is,

$$Y = f\,(\zeta_1, \zeta_2, ...\zeta_k) \qquad (1)$$

and response surface can take the different forms according to the function types of response and usually response function is defined in the quadratic polynomial form as follows.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum_i \sum_j \beta_{ij} X_i X_j + \varepsilon, \quad i \le j \qquad (2)$$

Where; Y is the response; β_0 is the intercept; β_i, β_{ii}, β_{ij} are the regression coefficients; X_i X_j are the coded variables; and ε is the error.

The coding of independent variables into X_i is expressed by the following equation:

$$X_i = \frac{\xi_i - \xi^*}{d_s} \qquad (3)$$

Where;

ξ_I is the actual value in original units; ξ^* is the average value (center point); and d_s is the step value.

The independent variables were milking system vacuum, pulsation rate and ratio and flow rate. Based on the principles of RSM and use of CCD, these independent variables were coded and using the coding equation given in equation 3, and necessary transformation of the variables were made.

The coded and uncoded levels of these variables are tabulated in Table 1. As seen from Table 1 and transformation equations given above, a step value of 7 kPa, 1.5 L min^{-1}, 12 cycles min^{-1} was considered for milking system vacuum, flow and pulsation rate, respectively while the center point for these variables was set to 44 kPa, 5 L min^{-1} and 65. Pulsation ratio center was selected as 62:38 and the step value was set to 0.306, which is the ratio of these two variables that sums up to 100.

A total of 30 experiments as significantly reduced number of runs as compared to full factorial experiments was carried out in the laboratory based on CCD and five levels of each independent variable were considered as seen from Table 2.

Eight vacuum related variables were measured as a function of four independent variables considered in this study. The measured variables were average vacuum at the teat end (V_t). average claw vacuum (V_c) and the vacuum drops in b-phase (D_b), d-phase (D_d) and claw (D_c) along with the fluctuations in b (F_b) and d phase (F_d) and also in claw (F_c).

The vacuum drops were determined as the difference between the system vacuum and teat-end vacuum at randomly selected from sequential 12 cycles. The results from the experiments were used to develop functions for each dependent variable. A general theoretical quadratic function including all possible interactions of four variables was defined and submitted to a statistical package program and stepwise regression procedure was applied in order to select the variables at a probability level of 95 %. The coefficient of determination value was used to assess the model fit.

Table 1. Coded and uncoded levels of independent variables used in experiments based on CCD

Çizelge 1. *Merkez esaslı (CCD) dizayna dayalı denemelerde kullanılan bağımsız değişkenlerin kodlu ve kodlanmamış değerleri*

Independent variables	Coded level				
	-2	-1	0	+1	+2
Milking system vacuum (kPa) -V	30	37	44	51	58
Pulsation ratio - P_r	50:50	57:43	62:38	66:34	70:30
Flow rate (L min^{-1}) - Q	2	3.5	5	6.5	8
Pulsation rate (cycles min^{-1}) - P_t	41	53	65	77	89

Table 2. Independent variables and measured vacuum related variables in experiments based on CCD
Çizelge 2. *Merkez esaslı (CCD) dizayna dayalı denemelerde kullanılan bağımsız değişkenler ve ölçülen vakum ilintili değişkenler*

Design point	Coded and uncoded independent variables				Measured vacuum related variables (kPa)							
	X_1 (V)	X_2 (P_r)	X_3 (Q)	X_4 (P_t)	V_m	V_{mc}	V_b	V_d	V_c	F_b	F_d	F_c
1	+1(51)	-1 (57:43)	+1 (6.5)	+1 (77)	45.4	46.2	5.4	5.3	4.7	1.9	1.8	4.1
2	+1(51)	-1(57:43)	-1(3.5)	+1(77)	48.3	48.4	2.3	2.6	2.5	2.1	1.7	3.5
3	-1(37)	+1 (66:34)	-1(3.5)	+1 (77)	35.0	34.9	1.9	3.3	2.0	6.3	4.3	6.7
4	+2 (58)	0 (62:38)	0 (5)	0 (65)	53.9	54.4	3.7	4.6	3.5	3.6	2.2	4.8
5	+1(51)	-1 (57:43)	-1(3.5)	-1(53)	48.7	48.8	2.2	2.3	2.1	2.8	2.3	3.3
6	+1 (51)	+1 (66:34)	-1(3.5)	-1(53)	48.6	48.5	2.3	2.9	2.4	6.1	3.9	6.5
7	0 (44)	0 (62:38)	-2 (2)	0 (65)	42.2	42.1	1.8	2.0	1.8	4.4	3.8	5.0
8	-1(37)	-1 (57:43)	-1(3.5)	-1(53)	34.7	34.6	2.3	2.6	2.3	4.0	3.0	4.5
9	+1 (51)	+1 (66:34)	+1(6.5)	-1(53)	46.6	46.6	3.9	5.7	4.3	7.7	4.1	8.1
10	0 (44)	+2 (70:30)	0 (5)	0 (65)	40.3	40.3	3.3	5.3	3.6	7.7	3.5	7.8
11	+1 (51)	+1 (66:34)	-1(3.5)	+1(77)	48.8	49.4	2.1	3.1	1.5	4.5	2.3	4.9
12	-2 (30)	0 (62:38)	0 (5)	0 (65)	26.9	26.8	3.1	4.3	3.1	7.1	3.3	7.3
13	-1 (37)	+1 (66:34)	+1(6.5)	-1(53)	32.8	32.9	3.4	6.4	4.1	10.0	4.7	9.5
14	-1 (37)	-1 (57:43)	+1(6.5)	-1(53)	33.2	33.3	3.8	4.5	3.6	5.2	3.1	6.5
15	+1 (51)	-1 (57:43)	-1(3.5)	+1(77)	48.9	48.8	2.3	2.0	2.1	2.1	1.4	3.2
16	+1 (51)	+1 (66:34)	+1(6.5)	+1(77)	46.2	46.4	5.1	5.8	4.5	5.5	1.7	6.1
17	-1 (37)	-1 (57:43)	-1(3.5)	+1(77)	34.6	34.6	2.4	2.7	2.3	2.7	1.6	3.4
18	-1 (37)	+1 (66:34)	+1(6.5)	+1(77)	32.8	32.8	4.2	6.0	4.1	8.7	2.3	7.8
19	0 (44)	0 (62:38)	0 (5)	-2 (41)	40.5	40.5	2.9	4.1	3.4	8.6	6.5	8.3
20	0 (44)	0 (62:38)	0 (5)	+2 (89)	40.5	40.7	3.3	4.2	3.3	3.6	1.8	4.9
21	-1 (37)	-1 (57:43)	+1(6.5)	+1(77)	32.7	33.1	4.3	4.8	3.8	3.4	2.0	5.5
22	0 (44)	-2 (50:50)	0 (5)	0 (65)	40.7	40.6	2.8	2.9	3.3	1.7	2.2	4.3
23	-1 (37)	+1 (66:34)	-1(3.5)	-1(53)	33.9	34.1	3.0	3.7	2.8	8.5	6.1	8.7
24	0 (44)	0 (62:38)	+2 (8)	0 (65)	37.9	38.3	5.8	7.5	5.6	6.5	3.0	7.5
25	0 (44)	0 (62:38)	0 (5)	0 (65)	40.2	40.1	3.8	4.5	3.8	5.6	3.3	6.0
26	0 (44)	0 (62:38)	0 (5)	0 (65)	40.8	40.9	3.1	3.9	3.1	5.7	2.8	6.2
27	0 (44)	0 (62:38)	0 (5)	0 (65)	40.4	40.5	3.5	4.5	3.4	5.4	2.5	6.1
28	0 (44)	0 (62:38)	0 (5)	0 (65)	40.4	40.4	3.8	4.2	3.5	5.6	3.2	6.1
29	0 (44)	0 (62:38)	0 (5)	0 (65)	40.3	40.5	3.5	4.7	3.4	5.2	2.9	5.9
30	0 (44)	0 (62:38)	0 (5)	0 (65)	40.2	40.5	3.8	4.5	3.4	5.6	3.0	5.9

RESULTS and DISCUSSION

Using the raw data obtained from the experiments conducted based on CCD as tabulated in Table 2. The following polynomial functions were developed from the data obtained in the laboratory. The functions given below are written in the order that the variables entered into the model so that the contribution order of the terms to the model could then be identified.

The function to predict teat-end vacuum (V_t):

$$V_t = 40.52 + 6.812X_1 - 1.058X_3 - 0.212X_1X_3 - 0.207X_3X_4 + 0.156X_2X_4 \qquad (R^2=0.998) \qquad (4)$$

The function to predict average claw vacuum (V_c):

$$V_c = 40.64 + 6.912X_1 - 0.973X_3 - 0.217X_1X_3 \qquad (R^2=0.998) \qquad (5)$$

The function to predict vacuum drop in b phase (D_b):

$$D_b = 3.627 + 0.984X_3 + 0.31X_3X_4 + 0.214X_1X_3 + 0.139X_1 - 0.148X_2^{\ 2} - 0.125X_4^{\ 2} + 0.136X_4 \quad (R^2=0.947) \qquad (6)$$

The function to predict vacuum drop in d phase (D_d):

$$D_d = 4.298 + 1.325X_3 + 0.507X_2 \quad (R^2=0.944) \qquad (7)$$

The function to predict vacuum drop in claw (D_c):

$$D_c = 3.362 + 0.966X_3 + 0.206X_1X_3 \quad (R^2=0.902) \qquad (8)$$

The fluctuation function in b and d-phase along with fluctuation in claw are in the following form:

The fluctuation function in b phase (F_b):

$$F_b = 5.597 + 1.741X_2 - 0.97X_4 - 0.831X_1 + 0.577X_3 - 0.4X_1X_2 - 0.224X_2^{\ 2} \quad (R^2=0.963) \qquad (9)$$

The fluctuation function in d phase (F_d):

$$F_b = 2.948 - 0.978X_4 + 0.495X_2 - 0.289X_1 + 0.279X_4^{\ 2} - 0.42X_2X_3 + 0.33X_1X_3 - 0.23X_3X_4 \quad (R^2=0.921) \qquad (10)$$

The fluctuation function in claw (F_c):

$$F_c = 6.071 + 1.209X_2 - 0.708X_4 + 0.678X_3 - 0.648X_1 - 0.27X_2X_4 \quad (R^2=0.938) \qquad (11)$$

Please note that the all of the above functions uses the coded level of the variables in the range of -2 and +2 as depicted in Table 1.

It should be stated here that no optimum point of any variable from the above written functions can be obtained by taking the partial derivative of a variable even though RSM is a methodology used for optimization and the find out the optimum of a variable.

The models are valid under the following conditions (in original units of the variables);

58 kPa ≥ V ≥ 30 kPa

70:30 ≥ P_r ≥ 50:50

8 L min^{-1} ≥ Q ≥ 2 L min^{-1}

89 cycles min^{-1}≥ P_t ≥ 41 cycles min^{-1}

where; V is the milking system vacuum. P_r is the pulsation ratio. Q is the flow rate and P_t is the pulsation rate.

One of the examples of the response surface with original units of the variables are depicted in Figure 2 even though many response surfaces can be generated as a combination of two independent variables.

As understood from examining equation 4, the values of the average vacuum at the teat end lie on all four variables. Milking system vacuum (X_1) and flow rate (X_3) entered the model as the main variables. The other variables are in interaction form. Similar to the average vacuum at the teat end, average claw vacuum function (equation 5) is also linearly correlated with two variables, milking system vacuum and flow rate. It could be stated that the first two functions, namely teat end vacuum and average claw vacuum have the highest coefficient of determination value (0.998) as compared to other functions developed in this study.

The vacuum drop function in b-phase has the most complicated structure among the models developed in this study as understood from equation 6. The function includes all four variables but only pulsation ratio (X_2) and pulsation rate (X_4) are in the quadratic form. Milking system vacuum and flow rate linearly affect the vacuum drop in b-phase. As seen from Figure 2, it could be stated that the highest vacuum drops in b-phase occurs when the pulsation ratio of 62:38 under the same system vacuum pressure. pulsation rate and flow rate while the milking system vacuum and pulsation ratio and other two variables affects the vacuum drops in d-phase linearly.

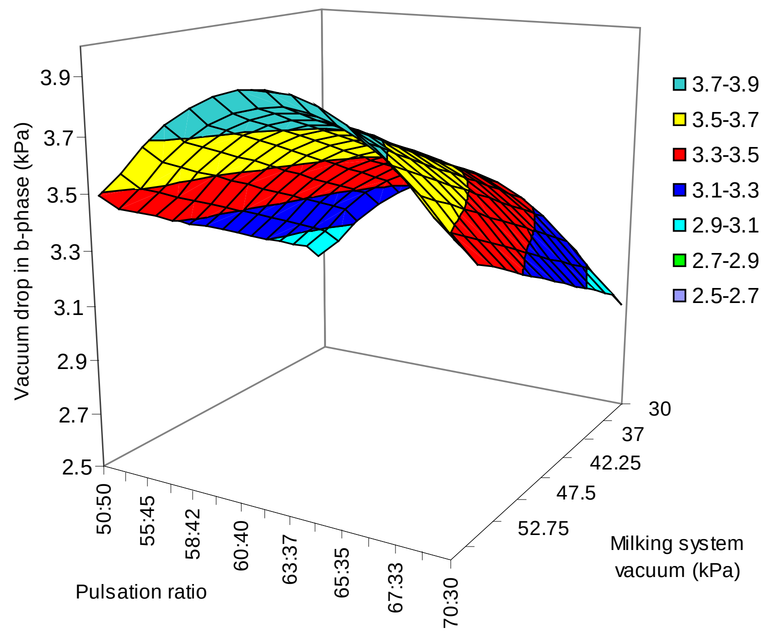

Figure 2. Vacuum drops (kPa) in b-phase of milking as a function of milking system vacuum and pulsation ratio (flow rate and pulsation rate are kept constant at the centre, zero level as in coded form).

Şekil 2. *Sağım sistem vakumu ve nabız oranının bir fonksiyonu olarak sağımın b fazındaki vakum düşüşleri (kPa) (debi ve nabız sayısı kodlu formda merkez değeri olan "0" olarak alınmıştır).*

Vacuum drop function in d-phase (equation 7) and in claw (equation 8) are simple and they form a linear surface while the vacuum drop function in claw has the lowest coefficient of determination value (0.902) among eight models developed in this study.

Once the fluctuation functions in b and d-phase and in claw are examined as given in equation 9 thru 11. It can be stated that all three functions have such a common point that all four variables affect fluctuations while the effect of pulsation ratio (X_2) and pulsation rate (X_4) has quadratic effect on fluctuation in b (equation 9) and d-phase (equation 10) respectively. On the other hand, the fluctuation in claw (equation 11) is a linearly related to all four variables.

CONCLUSIONS

The following conclusions were drawn from the study conducted:

- The simplest models for the four-way milking cluster are the ones that are developed for the average claw vacuum and the models developed for the vacuum drops in d-phase and claw since vacuum drop in d-phase is formed only by pulsation ratio and flow rate while the average vacuum and the vacuum drop models in claw are the function of only milking system vacuum and flow rate. The common point of these three models along with the average vacuum prediction function is that there is no quadratic or cubic term entered into the model and they all have a linear form.

- The highest vacuum drops in b-phase for four-way milking cluster occurs when the pulsation ratio of 62:38 under the system vacuum pressure ranging between 30-58 kPa once the pulsation and flow rates are kept constant.

- The system behavior for vacuum drops in d-phase is different than b-phase and a linear surface is valid for the interaction of flow rate and pulsation ratio when four-way milking cluster was used.

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