Application of Response Surface Methodology (RSM) to Evaluate the Performance of Controlling Parameters for Worm Gearbox under no-load condition

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ABSTRACT

Worm Gear drives are widely utilized for speed reduction and high torque multiplication in Industrial equipment. These drives are generally lubricated using splash lubrication. A large amount of energy is therefore expended not only in overcoming the metallic friction but also in overcoming the viscous drag (churning losses). The losses occur due to the dragging of viscous lubricant is called churning power loss. The Central Composite Design (CCD)-based Response Surface Methodology (RSM) was used to determine and optimize the churning power loss effect for worm gear. As the controlling variables, the input number of revolutions, lubricant volume, and lubricant temperature were taken into account. The test rig was designed and fabricated based on the simple direct torque measurement method to measure the churning loss of the worm gearbox. A developed model based on experiments was proposed to associate the independent parameters for minimizing the churning power loss for the worm gearbox at the optimum process condition. It is proved that the most effective parameter for this study was the lubricant temperature for the churning power loss of worm gearbox in comparison with other parameters. It may be due to the higher F-statistics value for churning power loss.

Keywords

Lubrication; Response Surface Methodology (RSM); Churning Power Loss (CPL); No-load dependant loss; single start worm gear

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Introduction

The worm gearbox is commonly used for self-locking capabilities and high reduction ratios[1]. The worm gears offer several advantages compared with other transmission modes, which allow a wide range of power transmission applications[2]. Load capacity by worm gear transmitters is determined with their geometry parameters and lubrication [3]. To satisfy the needs, the demands for more efficient gearboxes were increased. This can be achieved by reducing power losses. There are two types of power losses for gearbox, load dependant loss, and no-load dependant loss. The no-load dependent losses are further divided into churning losses, windage losses, and seal losses. The influence of churning losses on the efficiency of the worm gear reducer is presented in this paper. Energy losses when the gear is dragged in the lubricant under splash lubrication are called churning power loss [4]–[6]. The prediction method for churning power loss of worm gear is developed by using Response Surface Methodology (RSM). As the influencing parameters, the lubricant temperature, the input numbers of revolutions, variable immersion depth was taken for the experiment. Experimental tests were performed based on Response Surface Methodology. The literature survey above uncovers that most of the studies on gear efficiency are centered on the parallel axis of the gear. A couple of experimental studied devoted to examining churning power losses were constrained either to disc, a single, or a gear pair. In any case, regardless of whether broad studies are accessible on cylindrical gears, it shows up from this condition of art that almost no or no experimental information concerning churning losses produced by worm gears are accessible in literature. The primary reason for this examination was to build up a database through firmly controlled analyses with an end goal to measure the commitments of the segments of churning power losses for worm gear. With this point, worm gear test rig developed to initially explore the impact of worm shaft speed, the temperature of the lubricant, and the level of lubricant on total churning losses of a worm gear pair.

Experiment work

There are three ways to determine the churning losses in dip lubrication for gearboxes: heat dissipation measurement, direct torque measurement from torque sensor, and inertia run-down method[7]. The experiment test rig based on the direct torque measurement technique is shown in Figure 1. The experimental set-up was developed to measure the input torque of the worm shaft and the setup consists of the following components. Worm gearbox having variable reduction ratio, AC motor with the specification of 3 phase, 3 HP and 1440 rpm, Variable frequency drive was used to vary the speed of the motor, Temperature sensor to measure the temperature of oil inside the gearbox, Optical type rotary torque sensor with a precision of ±0.01Nm, a Pressure gauge to measure the pressure of the air inside the gearbox, the Level indicator was used to measure the level of oil. The complete set up was mounted on the test machine as shown in Figure 1[3], [8].

The inside volume of the gearbox was kept constant (180mm×180mm× 280 mm). According to the volume inside the gearbox, a certain volume of oil was included in this gearbox. The torque sensor measured the input torque and variable frequency drive read the rotation speed which helped to compute the input power of the gearbox. The power loss P (Immersed) was first estimated when the worm and worm wheel were immersed/partially in oil and turned at a specific speed. At that point, the power loss P (Non Immersed) was estimated when the worm and worm wheel was not immersed in oil and pivoted at a similar revolution speed. For the non-immersed condition, the gear work area and the bearing area were provided with a small amount of oil, Assuming the friction power loss estimates were roughly equivalent for both conditions [9], [10].

P (Immersed) = Pwf + Pwc + Pbf + Pbc + PsP
(Non immersed) = Pgf + Pbf + Ps

Where Pwf is the worm and worm wheel's friction power loss, Pwc is the worm and worm wheel's churning power loss, Pbf is the bearing's friction power loss, Pbc is the bearing's churning power loss, and Ps is the oil seal power loss. Under both lubrication conditions, the disparity in power loss was due to the churning loss of gears and bearings [10], [11].

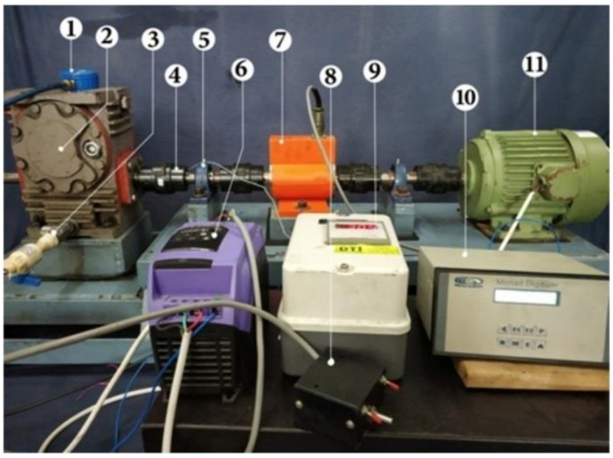


Fig.1. Test rig of worm gearbox for both position of the worm

1-Pressure Gauge,2-Worm gearbox,3-Provision for oil level indicator,4-Jaw type coupling,5-Foot mounted bearing,6-Variable frequency drive (VFD),7-Torque sensor,8-VFD regulator,9-Temperature indicator,10-Digital controller for Torque sensor and 11-3 phase AC motor.

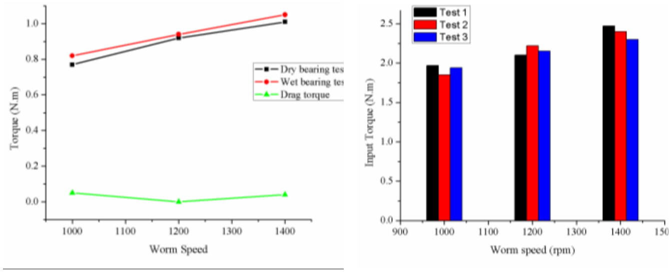
P (Churning) = P (Immersed) - P (Non immersed)

Where P (churning) is the churning power loss in the gearbox. For that, input torque was measured with various controlling factors as per test matrix, simultaneously input torque was calculated with non immersed condition with same speed. The difference between the immersed and non immersed torque shows the churning torque.

When working gearbox with minimum acceptable shaft diameter with the condition of immersed bearing and condition of the non-immersed bearing. The measured torque loss represents primarily churning power loss of bearing and shaft, the latter churning loss of shaft being negligible because of a very small diameter. This arrangement was utilized to decide the churning power losses of the input shaft bearings. The first test, called the dry bearing test, represented experiments in which no oil was present inside the gearbox. The second test, known as the wet bearing test, aimed at representing experiments where oil volume greater than or equal to 1.5 lit. In this condition, both bearings were submerged into the oil.

It is seen from Figure 2 (a) that drag-torque loss of bearing and seal loss is comparatively very less and it can be negligible. Thus the total churning power loss of gearbox Pgc is equivalent to churning power loss P churning of worm gear pair.

P (Churning) ≈ Pgc



(a) **(b)**

Fig.2. (a) Measured bearing & oil seal torque loss (b) Repeatability of churning loss measurement for worm gear pair at 50 ºC, 2.1 volume.

Three experiments per set have been taken at different time to investigate the repeatability of dip lubricated the worm gearbox. The repeatability of result is acceptable and the average error is 6.5% about mean value as shown in figure 2(b).

(a) **(b)**

Fig.3. (a) Temperature sensor and its arrangement, (b) Test gear pair [3]

Table 1. Worm gear geometric properties

Gear	Worm Wheel	Worm Shaft
Number of teeth	30	Single start
Material	CuSn12	16MnCr5
Module (mm)	3	
Pressure angle	20	
Centre distance (mm)	75	
OD(mm)	132	40
Reduction ratio	30.:1	

The temperature of the oil was also monitored during the test with the help of a temperature sensor as shown in Figure 3(a) and a single start worm and worm wheel were selected as a test gear pair as shown in Figure 3(b). Geometrical dimensions of single start worm and worm wheel are given in Table 1.

Generally, industrial worm gearboxes are used with mineral oil and synthetic oil [12]-[13]. PAO (Polyalphaolefin) PAO or PAG (polyalkylene glycol) PAG synthetic oils have become lubricants of choice for many worm gear as well as other gear applications due to their friction-reducing and extended life characteristics[12]-[14]. Synthetic lubricant (PAO) was used for the experiments and its characteristic is resumed in Table 2.

Table 2. Lubricant properties

Sr. No	**Name of oil**	**Kinematic Viscosity (cSt) @ 40 °C**	**Kinematic Viscosity (cSt) @ 100 °C**	**Viscosity Index**	**Density (Kg/m^3) @ 15 °C**
1	Synthetic oil – PAO grade 320	330	35.50	162	790

All the experiments were performed based on the Direct Torque Measurement Technique and designed with the help of the RSM. The RSM (Response Surface Methodology) is a mixture of both statistical and quantitative approaches, which is used to select the best test conditions requiring the least number of tests to obtain adequate results[15]. The Present work is designed with central composite design (CCD) to investigate the churning power loss of worm gearbox. The gearbox was surrounded by insulation to avoid the blocks in CCD[16]-[17]. For three variables in the experiments, six axial points, six replicates at the central points and eight factorial points were used for the CCD design [15]-[16].

The worm speed, volume of lubricant, and temperature of the lubricant were chosen as factors in the CCD to investigate the churning power loss for worm gearbox. Their level had been selected based on pilot experiments and literature reviews. As a response, the churning power loss was chosen. Each variable was analyzed at five different levels: −α, −1, 0, +1, and +α, as shown in Table 3 (α value was fixed at 1.6817 for rotatable) [17]–[21].

The response (churning power loss) of the experiments are shown in Table 4. The performance of the churning power loss is explained by the second-order polynomial model as given in equation (5).

$$CPL=Y_0+Y_1A+Y_2B+Y_3C+Y_{12}AB+Y_{13}AC+Y_{23}BC+Y_{11}A^2+Y_{22}B^2+Y_{33}C^2 \quad (5)$$

Here Y_0 Y_{12}, Y_{13}, and Y_{23} are the coefficient for the interception, Y_{11}, Y_{22}, and Y_{33} are the quadratic terms, and Y_1, Y_2, and Y_3 are the independent variables [16].

Table 3. The level of independent variables for the experiments

Independent Variable	**Symbol**	**Level of Coded variable**				
		-α	**Low**	**Medium**	**High**	**+α**
		-1.6817	-1	1	+1	+1.6817
Worm speed (rpm)	A	764	900	1100	1300	1436
Lubricant Volume (lit.)	B	1.1	1.5	2.1	2.7	3.1
Lubricant Temperature (°C)	C	36.6	40	45	50	53.41

Table 4. The design of experiments with their observed and predictive values.

Std run no	**Run**	**Independent Variable in Coded Form**			**Experiment work**		**Churning Power Loss (watt)**		
		A	***B***	***C***	***Input torque***	***Churning torque***	***Observed***	***Predicted***	***Residuals***
5	1	-1	-1	1	1.72	0.32	15.08	15.27	-0.19
13	2	0	0	-α	2.86	1.39	80.06	73.11	6.95
10	3	+α	0	0	2.87	1.13	84.98	75.18	9.80
12	4	0	+α	0	2.37	0.9	51.84	45.77	6.07
19	5	0	0	0	2.46	0.99	57.02	57.23	-0.21
8	6	1	1	1	2.25	0.62	42.2	46.13	-3.93
18	7	0	0	0	2.5	1.03	59.32	57.23	2.09
9	8	- α	0	0	2.13	0.78	31.19	30.51	0.68
16	9	0	0	0	2.41	0.94	54.14	57.23	-3.09
17	10	0	0	0	2.48	1.01	58.17	57.23	0.94
14	11	0	0	+α	1.94	0.47	27.07	23.55	3.52
3	12	-1	1	-1	2.38	0.98	46.18	48.22	-2.04
7	13	-1	1	1	1.93	0.53	24.98	24.83	0.15
4	14	1	1	-1	2.88	1.25	85.08	89.50	-4.42
6	15	1	-1	1	1.99	0.36	24.5	27.12	-2.62
20	16	0	0	0	2.48	1.01	58.17	57.23	0.94
1	17	-1	-1	-1	2.04	0.64	30.16	30.84	-0.68
15	18	0	0	0	2.51	1.04	59.9	57.23	2.67
11	19	0	-α	0	1.81	0.34	19.58	15.17	4.41
2	20	1	-1	-1	2.48	0.85	57.86	62.67	-4.81

The statistical software "Design-Expert 10" was used to study the regression analysis of experimental data and also used to plot the graph. The analysis of variance (ANOVA) was used to analyze the significance of the statistical parameters[17]. The 95% confidence level ($\alpha = 0.05$) was used in all analyses to determine statistical significance.

Results & Discussion

Results were evaluated using different descriptive statistics, such as F-value, p-value, and degree of freedom (df). As shown in Table 5, the low probability value ($p < 0.001$) indicates that the model was highly significant and could be used to accurately predict the response function.

Table 5. ANOVA result for the developed model.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	Remark
Model	8232.3	9	914.7	31.29	< 0.0001	significant
A-worm speed	2471.07	1	2471.07	84.54	< 0.0001	significant
B-lubricant volume	1145.85	1	1145.85	39.2	< 0.0001	significant
C-lubricant temperature	2977.11	1	2977.11	101.86	< 0.0001	significant
AB	45.13	1	45.13	1.54	0.2424	
AC	199.6	1	199.6	6.83	0.0259	significant
BC	30.58	1	30.58	1.05	0.3305	
A2	34.57	1	34.57	1.18	0.3023	
B2	1289.57	1	1289.57	44.12	< 0.0001	significant
C2	142.71	1	142.71	4.88	0.0516	
Residual	292.28	10	29.23			
Lack of Fit	271.29	5	54.26	12.92	0.0069	significant
Pure Error	21	5	4.2			
Cor Total	8524.58	19				

The 31.29 Model F-value proposes the model is significant. The "Prob > F" values of less than 0.05 suggest the terms of the model are significant. In this case, A, B, C, AC, B2 are significant model terms. It shows the lubricant temperature is more significant than other parameters. The "Lack of Fit F-value" of 12.92 means the Lack of Fit is significant.

The experimental data for churning power loss are suited well with the predicted value of the model. For this model, the standard deviation was 5.41. Table 6 shows the statistical parameters obtained from ANOVA. The values of R2 and adjusted R2 (Radj) values are found to be 96% and 93% respectively. The value of R2 suggests to what degree the experimental data points can be estimated for the perfect model. The adjusted R2 calculated the amount of mean-variance described by the model. As shown in Table 6 the difference between predicted R-square and adjusted R-square is less than 0.2. So this model is significant. The equation (6) shows the final empirical model in terms of a coded factor for churning power loss of worm gearbox.

Table 6. Statistical factors obtained from ANOVA for churning power loss.

Insignificant factors excluded	Churning Power Loss
Std. Dev.	5.41
Mean	48.37
Coefficient of variance (C.V) %	11.18
R-Squared	0.9657
Adj R-Squared	0.9349
Pred R-Squared	0.7556

The Churning power loss (CPL)=58.0398 + 13.4514 * A + 9.15984 * B -14.7646 * C + 2.375

* AB + -4.995 * AC + -1.955 * BC + -1.5488 * A^2 + -9.45956 * B^2 + -3.14686 * C^2 (6)

The actual factors with the appropriate units can be used to make predictions about the response as given in equation (7). The predicted values of churning power loss by using equation (7) are shown in Table 4.

CPL= -595.863 + 0.335653 * Worm speed (rpm) + 133.182 * Lubricant volume (lit.) + 15.2388* Lubricant temperature (C) + 0.0197917 * Worm speed (rpm) * Lubricant volume (lit.) + -0.004995 * Worm speed (rpm) * Lubricant temperature (C) + -0.651667 * Lubricant volume (lit.) * Lubricant temperature (C) + -3.872e-005 * Worm speed (rpm)2 + -26.2765 * Lubricant volume (lit.)2 + -0.125874 * Lubricant temperature $(C)^2$ (7)

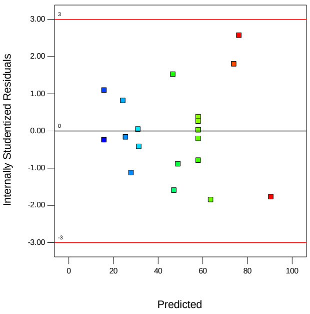
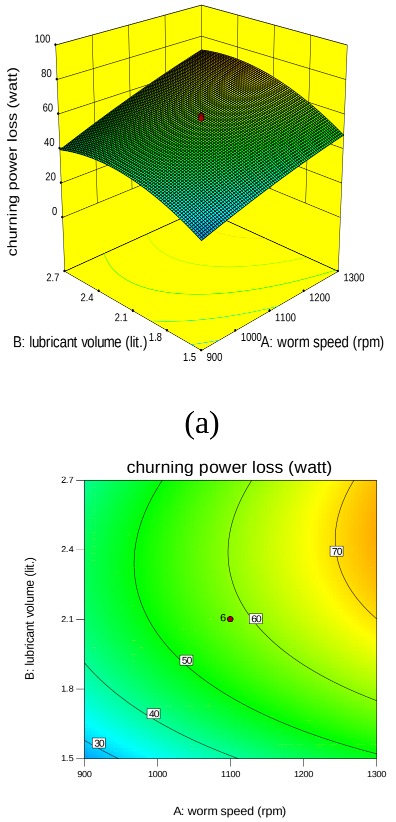


Fig.4. Internally studentized residuals versus predicted plot

The obtained equation with multiple variables can be used to predict the churning power loss within the limits of the experimental factors. Figure 4 shows the predicted churning power loss versus internally studentized residuals. The random scatter plot and the variance of the original observation are constant for all the response values, which shows that the transformation of the response variables was not required.

Combined effect of lubricant volume, lubricant temperature & Worm speed

The individual and interaction effects of controlling parameters for worm gearbox were investigated by using the response surface methodology. The following Figures show the 3-D response & 2-D contour effect of the input parameters on the churning power loss. Figure 5 indicates the interaction effect of lubricant volume and lubricant temperature on CPL at worm speed 1100 rpm by using surface plot and contour plot. The CPL is increasing with increasing lubricant volume and decreasing the Lubricant temperature. The maximum CPL was obtained 71.39 and minimum CPL was obtained 24.36. The interaction of lubricant volume & lubricant temperature is not significant as per the table 5.

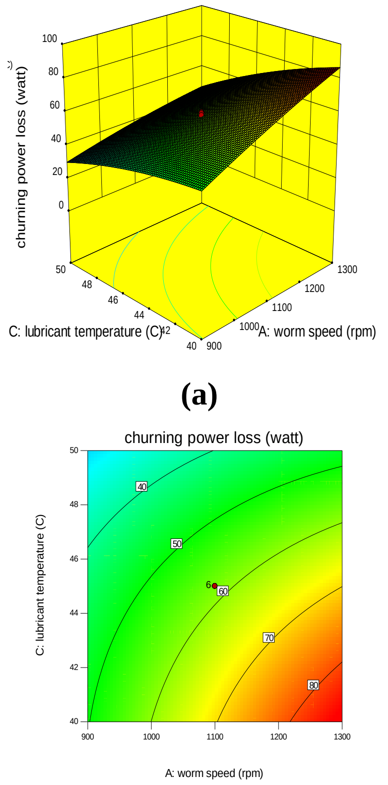


(a)

(b)

Fig.5. Effects of Lubricant Volume & Lubricant Temperature on churning power loss (CPL) (a) 3-D surface plot (b) 2-D contour plot

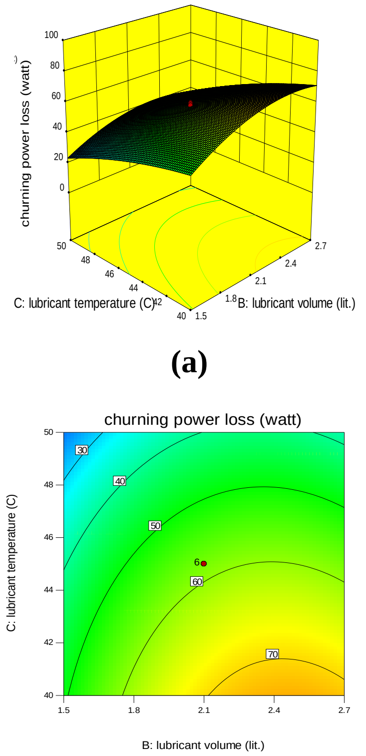
The interaction effect of worm speed and lubricant temperature on CPL at lubricant volume 2.1 lit as shown in Figure 6. The CPL is increasing with increasing of worm speed and decreasing the Lubricant temperature. The maximum CPL was obtained 85.72 and minimum CPL was obtained 31.57. This interaction is more significant than others.



(a)

(b)

Fig.6. Effects of Worm speed & Lubricant Temperature on churning power loss (CPL) (a) 3-D surface plot (b) 2-D contour plot



(a)

(b)

Fig.7. Effects of Lubricant Volume & Lubricant Temperature on churning power loss (CPL) (a) 3-D surface plot (b) 2-D contour plot

Figure 7 presents the interaction effect of lubricant volume and lubricant temperature on CPL at worm speed 1100 rpm. The CPL is increasing with increasing lubricant volume and decreasing the Lubricant temperature. The maximum CPL was obtained 71.39 and minimum CPL was obtained 24.36.

Confirmation Test

Confirming the suitability of the model to predict the minimum churning power loss (response function), a new experiment has been carried out using the optimum levels, as shown in Table 7.

Table 7. Comparison of the predictive and the experimental value of churning power loss for worm gear

Parameters	**Optimum Conditions**
Worm Speed (rpm)	903
Lubricant Volume (lit)	2.14
Lubricant Temperature (°C)	45.6
Predicted CPL (watt)	42.49
Experimental CPL (watt)	41.07
Error (%)	3.34

At the optimum values of parameters, the predicted value for the CPL was obtained as 42.49 and the observed value was 41.07. The comparison of the observed results with the predicted results indicates that the error was 3.34%, which is quite less. From the analysis, it has been concluded that the established model could predict the CPL accurately.

Conclusion

The CCD based RSM has been used to optimize the churning power loss effect for worm gear. It was found that churning power loss increases as worm speed, lubricant volume, and lubricant temperature rise decrease. It was found that the lubricant temperature and worm speed are the most effective parameters of churning power loss. The RSM based on CCD being a powerful apparatus in the enhancement of the churning power loss for worm gear. The good performance of the worm gearbox can be achieved with the optimized parameters. The optimal conditions found for the churning power loss for test gearbox were worm speed 903.78 rpm, lubricant volume 2.14 lit. and lubricant temperature 45.6 oC for the test gearbox. The empirical model was developed with the help of the Response Surface Methodology (RSM) technique. The established models are adequated and The values foreseen are in good agreement with the calculated results. The churning power loss of any kind of worm gear can be calculated using the model which has been developed. According to it, the churning loss can be reduced by selecting optimized controlling parameters.

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