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APPLICATION OF BOX-BEHNKEN DESIGN FOR THE OPTIMIZATION OF STEAM TURBINE EFFICIENCY

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ABSTRACT

In order to contribute to the development of a steam turbine locally, a ten (10) megawatt steam turbine was designed for power generation. MATLAB was used to develop simulation program for a two stage turbine with re-heater and regeneration Rankine cycle. Box–Behnken response surface methodology with three-level-three factor central composite design was used to investigate the effects of re-heat pressure, first feed pressure and second first water pressure on the efficiency of the turbine. Re-heat pressure between 0.5-3.0 MPa, first feed pressure of 0.70- 1.20 MPa and second first water pressure of 0.1-0.5 MPa were employed in the simulation experiment. Optimization technique predicted 42.3% the efficiency of 10 MW steam turbine designed.

KEYWORDS: Design, Optimization, Simulation, steam turbine.

1.0 INTRODUCTION

Steam turbine is widely used for power generation due to its numerous advantages. For its design, a thermodynamics model for performance prediction is usually an initial step. The model can be used to predict performance base on the selected operating parameters such as pressure and temperature at different stages of the turbine. Improving thermal efficiency of the steam turbine by the use of super-heaters, re-heater and regenerators is discussed in several literatures.[1-5] Modern steam turbines are designed with improved efficiency by incorporating several feed water heaters at predetermined optimum pressures and temperatures. Best operating conditions are desired as this has direct effect on the cost and turbine life. Consequently, steam turbine design engineers use computer program to determine optimum operating pressures of respective feed water heaters for improved performance.

Several methods have been applied to optimize turbine performance base on operating parameters. Some researchers have developed optimization models for such purposes.[6-7] However, most of such models are limited in application.[7] proposed an optimization model. His model is suitable for paper mill power plant. Several other authors have reported the optimization of steam turbine performance.[8] Their results are relevant to the development of operational policies rather than improving the turbine performance at the design level.[9] optimized steam turbine stage efficiency with a genetic algorithm. Their results indicated that the new method accurately shows the optimal geometric and aerodynamic parameters of the stage for maximum efficiency.[10] applied exergy approach to optimize a steamturbine cycle. They remarked that the technique will further assist power engineers in utilizing energy resources.[11] patent an approach for optimizing the efficiency of a steam turbine. His approach is based on the adjustment of the throttle of steam pressure of a steam. Not much has been reported on the application of optimization tools in determination of optimum pressures for best performance during the design stage of a steam turbine.

The Response Surface Methodology (RSM) is a statistical and mathematical technique that can be used to improve and optimize processes. Importantly, it can be applied to design, development and formulation of new products, as well as to the improvement of existing product designs. The most extensive applications of such methodology are in the industrial world particularly in situations where several input variables potentially influence some performance measure or quality characteristic of the product or process. The RSM tends to model the response base on a group of experimental factors and then determine the optimal settings of the experimental factors that maximize or minimize the response.

So far, no published work has been reported on optimization of efficiency of steam turbine using the RSM method. This work presents the use of Box–Behnken response surface methodology in the optimization of the turbine efficiency for a designed of two stage re-heat and regenerative cycle ten (10) megawatt steam turbine.

2.0 MATERIALS AND METHOD

2.1 The proposed Steam Turbine

A modern two stage re-heater steam turbine with respective feed-water system in each turbine stage discussed in[12] was adopted for this work. The schematic representation of the experimental apparatus and T-S diagram are depicted in Figure 1 and 2, respectively. It is a re-heat–regenerative vapor power cycle with two feed-water heaters; a closed feed-water heater and an open feed-water heater is used in the design.

Steam entered the first turbine at 10MPa and 500°C and expands to 0.7MPa. The steam is reheated to 450°C and then channelled to the second turbine where it expands to a condenser pressure of 0.008MPa. Reheat pressure in the range of 0.5 to 3 MPa was investigated in this study. Steam is bled out into the closed feed water heater at a pressure varied between 0.7-1.2 MPa for this study. Feed water leaves the closed heater at 200°C and 8MPa (boiler pressure). Condensate exits as saturated liquid at 2MPa, and is tapped into the open feed water heater. Steam extracted from the second turbine at (pressure varied between 1 to 0.5MPa in this study) is also fed into the open feed water heater which operates at 3MPa. The steam exiting the open feed water heater is saturated liquid at 0.3MPa. The net power output of the cycle is 10 MW as estimated power to be designed for.

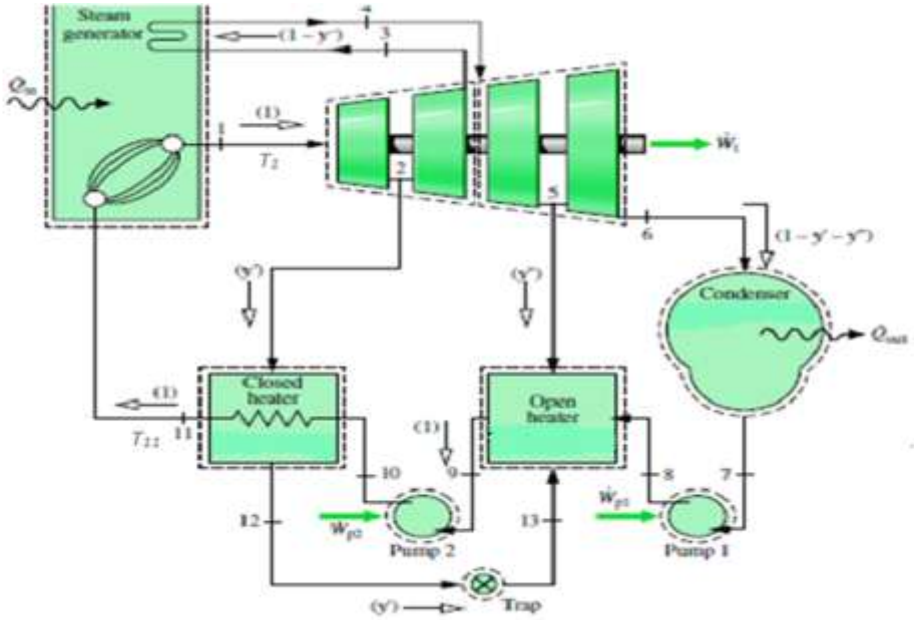

Fig. 1: Schematic diagram for steam turbine[1]

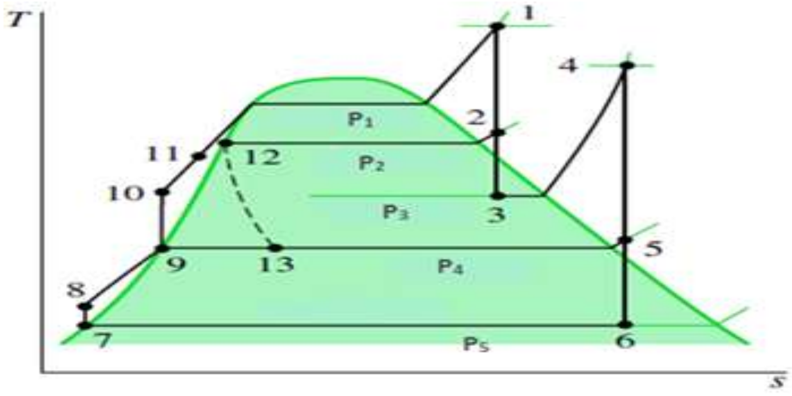

Fig 2: T-S diagram.

2.2 Simulation of Performance Parameters for Steam Turbine

A MATLAB program developed earlier[12] was employed for the simulation experiments. The program is designed to calculate the performance parameters and give as output desired performance parameter (which is efficiency for this study). The program input are predetermined enthalpies for desired operating parameters such as inlet pressure, inlet temperature, different stages of pressures, exit pressure.

The codes used to calculate the efficiency of the steam turbine are expressed in Equations 1-9.

$$\eta = (wt1)/m + (wt2)/m - (wp1)/m - [(wp2)/m \div Qin/m] \quad (1)$$

$$(wt1)/m1 \; = h1 - h2 + (1 - y1)\,(h2 - h13) \quad (2)$$

$$(wt2)/m2 \; = (1 - y1)\,(h4 - h5)(1 - y1 - y)\,(h5 - h6) \quad (3)$$

$$Y1 = ((h11 - h10\,))/((h2 - h12)) \quad (4)$$

$$Y = [(1 - y1)h8 + (y1 \times h13\,) - h9\,]/((h8 - h5)) \quad (5)$$

$$(wp1)/m = (1 - y1 - y)\,(h8 - h7) \quad (6)$$

$$(wp2)/m = (h10 - h9) \quad (7)$$

$$Qin/m = (h1 - h11) + (1 - y1)\,(h4 - h3) \quad (8)$$

$$M1 = [wcycle \div ((wt1)/m1\,)] + [(wt2)/((m - wp1)(m - wp\_2)m1\,)] \quad (9)$$

where wt_1/m and wt_2/m are the work delivered by the first turbine and second turbine per unit mass, respectively while wp_1/m and wp_2/m and Qin/m represent work done by the first pump, second pump and total heat added as a result of boiling and re-heating processes, respectively. The '*h*'s in the equations are predetermined enthalpies for respective stages in the plant cycle represented by a number index after it. y1 and y2 and the fraction of steam extracted into the first and second close feed water heaters, respectively.

2.3 Box-Bohnken Experimental Design

The box-bohnken experimental design, with three parametes, was utilized to investigate the response pattern and to determine the optimum combination of parameters. The influence of the (re-heat pressure (mpa), b (first feed pressure (mpa) and c (second first water pressure) at three variables levels in the turbine operation is presented in Table 1. A total of 17 simulation experiments were conducted separately for finding the experimental response of turbine efficiency. The re-heat pressure (mpa), first field pressure (mpa) and second first water pressure (mpa) were the independent parameters chosen for the optimization. The coded and un-coded levels of the independent parameters employed for the steam turbine are given in Table 1.

Table 1: Coded and actual variables used for the experimental design.

Parameters	Symbols	Levels		
		-1	0	1
Re-heat pressure	A	0.5	1.75	3
First feed pressure	B	0.7	0.95	1.2
Second feed water pressure	C	0.1	0.3	0.5

2.4 Statistical Analysis

The regression and graphical analysis were conducted with the Design Expert 6.06 software. The maximum values of steam turbine were selected as the response of the design experiment for the turbine operation. The experimental data obtained by the procedure mentioned earlier were analyzed by surface regression polynomial expressed in Equation (10).

$$Y_{(predict)}=\beta_o+\sum_{i=1}^{k}\beta_i x_i+\sum_{i=1}^{k}\beta_{ii} Xi^2+\sum_{j>1}^{k}\sum_{j=1}^{k}\beta_{ij} X_i X_j+e \qquad (10)$$

where $Y_{(predict)}$ is the predicted response variable (efficiency of turbine)

$\beta_0, \beta_1, \beta_{ii}, \beta_{ij}$ are regression coefficients; k is the number of factors studied and optimized in the experiment and e is the random error.

3.0 RESULT AND DISCUSSION

3.1 Response surface modelling

The experimental and predicted values for turbine efficiency (response) at the design points and all the three parameters in un-coded form are presented in Table 2.

The predicted equation for the estimation of predicted values of efficiency of the steam turbine is expressed in equation (11). It has a precision value of 5.765, F-value of 1.80 and an R-value of 0.8976. As thus, the model can be used to navigate the design space and it is independent of noise and the experimental values is adequately fitted by the generated equation.

$$0.353-0.05A+0.02B-0.12C-0.009A^2-0.16B^2+0.25C^2+0.072AB-0.006AC-0.0065BC \quad \textbf{(11)}$$

Table 2: Responses for steam turbine.

A: Re-heat pressure	B: First feed water pressure	C: Second feed water pressure	Steam turbine efficiency (%)	
			Experimental response	**Predicted response**
0.5	0.7	0.3	0.4153	0.416225
3	0.7	0.3	0.3262	0.350725
0.5	1.2	0.3	0.4187	0.394175
3	1.2	0.3	0.4191	0.418175
0.5	0.95	0.1	0.4071	0.42065
3	0.95	0.1	0.413	0.40295
0.5	0.95	0.5	0.4197	0.42975
3	0.95	0.5	0.4195	0.40595
1.75	0.7	0.1	0.4189	0.404425
1.75	1.2	0.1	0.4168	0.427775
1.75	0.7	0.5	0.4221	0.411125
1.75	1.2	0.5	0.4187	0.433175
1.75	0.95	0.3	0.4188	0.4188
1.75	0.95	0.3	0.4188	0.4188
1.75	0.95	0.3	0.4188	0.4188
1.75	0.95	0.3	0.4188	0.4188
1.75	0.95	0.3	0.4188	0.4188

3.2 Effect of Operating Variables on Steam Turbine Efficiency

Figure 4 shows the effect of second feed water pressure, first feed water pressure and re-heat pressure on the steam turbine efficiency (STE). It was observed that the STE increases with increase in second field water pressure. ET also increases with increase in first feed water pressure. ET increases with increase in re-heat pressure initially and decreases at higher re-heat pressure. This may be attributed to a reduction in flow losses which increase the turbine efficiency.[13] Presented in Figure 1 is the relationship between the predicted and actual efficiency of steam turbine. The graph demonstrated that the predicted values are very close to that of the experiment, demonstrating the reliability of the model and establishing the reliability of a correlation between the performance parameters and the efficiency of the steam turbine.

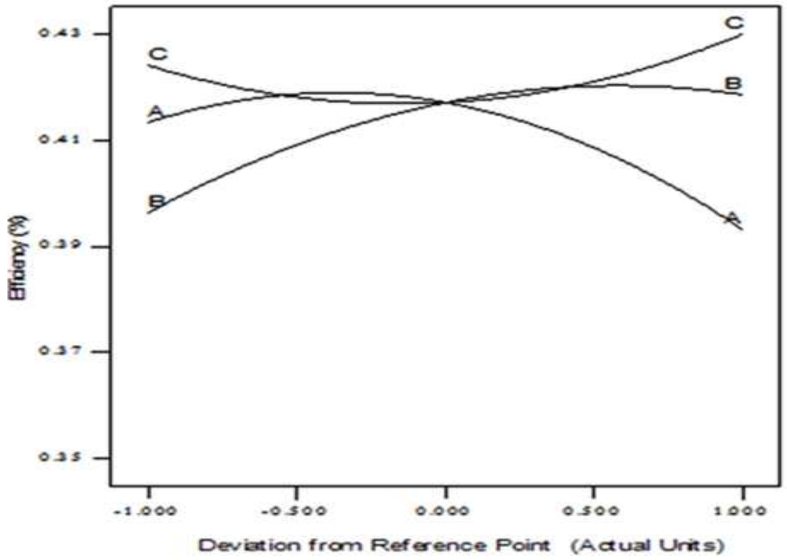

Fig. 4: Effect of re-heat pressure, first feed water pressure and second water feed water pressure on the efficiency of turbine. (RHP = 1.75, FFWP = 0.95, SFWP = 0.30)

3.3 The Effects of Operation Parameters on Steam Turbine Efficiency

Figures 5-7 present the response surface plots and steam turbine efficiency as a function of two parameters, while the third variable was kept constant. These graphs are appropriate for optimizing parameters as they enable defining the optimal conditions for achieving the maximum steam turbine efficiency (STE).

3.4 Effect of First Feed Water and Re-heat Pressure on Steam Turbine Efficiency

Figure 5 shows the response surface plot of the STE for the combined re-heat pressure (RHP) and first field water pressure (FFWP) at the medium value of second field water pressure (SFWP) (0.30 MPa). As it can be noticed in Figure 5, at low value of FFW, the STE increased with an increment in the value of RHP and then decreased sharply. At the higher value of FFWP, the STE showed similar behavior with a smoother decreasing rate. The results pointed that to get higher TSE at all value of FFWP.

RHP near medium value is preferred. At a low RHP, variations of TSE increased with increasing FFWP. The increasing rate of TSE is very favorable at the medium of RHP.

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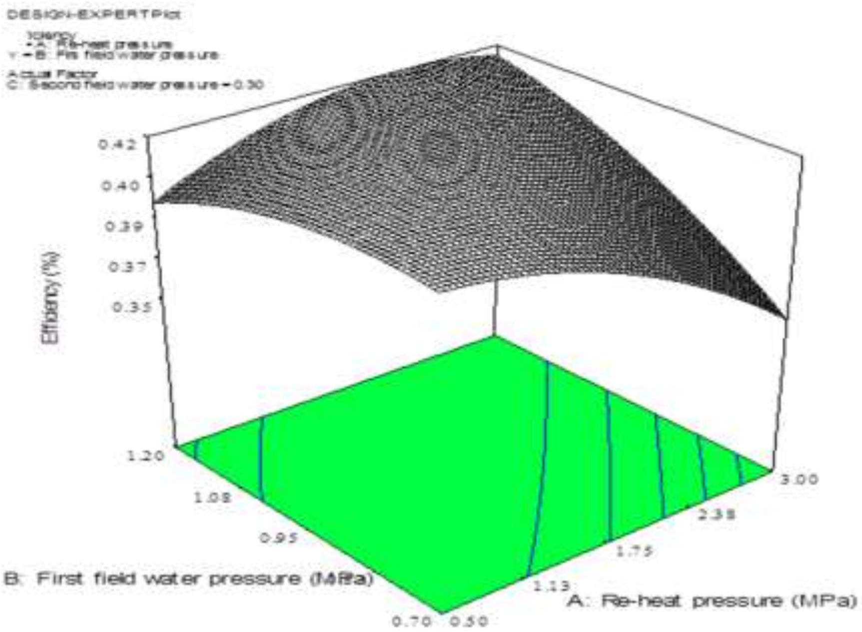

Fig. 5: Response surface of steam turbine efficiency with pre-heat pressure and first field water pressure.

3.5 Effect of Re-heat Pressure and First Feed Water on Steam Turbine Efficiency

Figure 6 demonstrates the impacts of re-heat pressure (RHP) and second field water pressure (SFWP) on the TSE. It was noticed that at low value of SFWP, the TSE slightly increased with the RHP increasing. The STE increased as the RHP increased. Hence, RHP is effective for maximum STE.

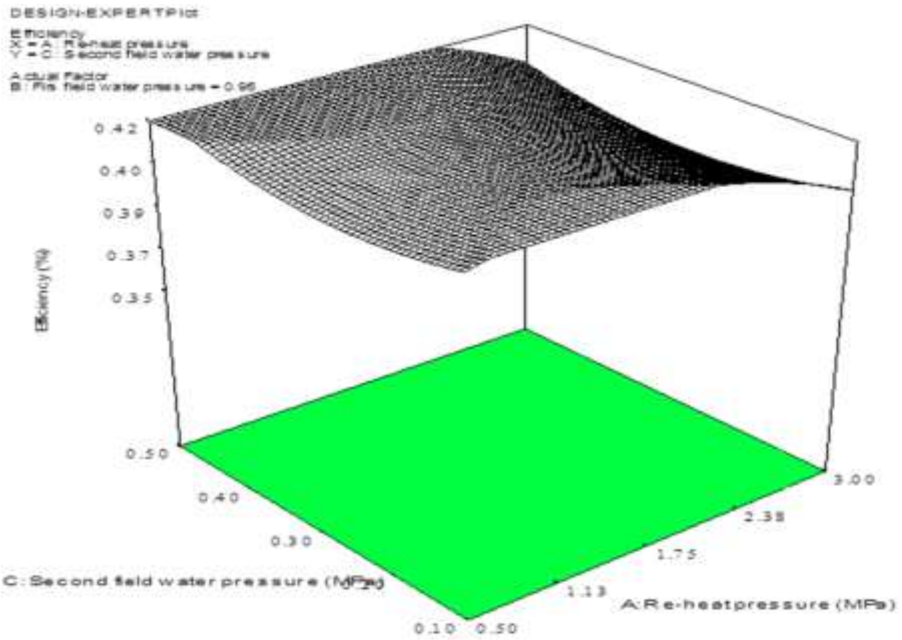

Fig. 6: Response surface of steam turbine efficiency with pre-heat pressure and second field water pressure.

3.6 Effect of first feed water and second feed water on steam turbine efficiency

Figure 7 presents first field water pressure (FFWP) and second field water pressure (SFWP) on steam turbine efficiency (STE) while keeping the pre-heat pressure at the medium value (1.75 MPa). At low level of SFWP, the STE increased with increasing FFWP. Moderate FFWP and SFWP is effective RHP near medium value is preferred. At a low RHP, variations of TSE increased with increasing FFWP. The increasing rate of TSE is very favorable at the medium of RHP.

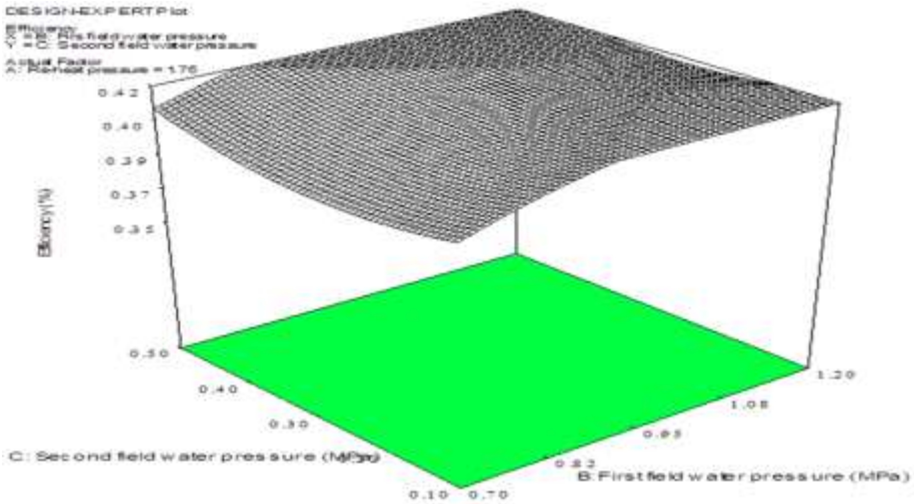

Fig. 7: Response surface of steam turbine efficiency with first field water pressure and second field water pressure.

4.0 Optimization of response parameters

The optimal operation conditions were calculated by regression model equation (2) according to the limit criterion of steam turbine efficiency maximization as presented in Figure 8, viz. re-heat pressure: 1.82 MPa, first field pressure: 1.11 MPa, second field water pressure: 0.32 MPa which led to steam turbine efficiency of 42%.

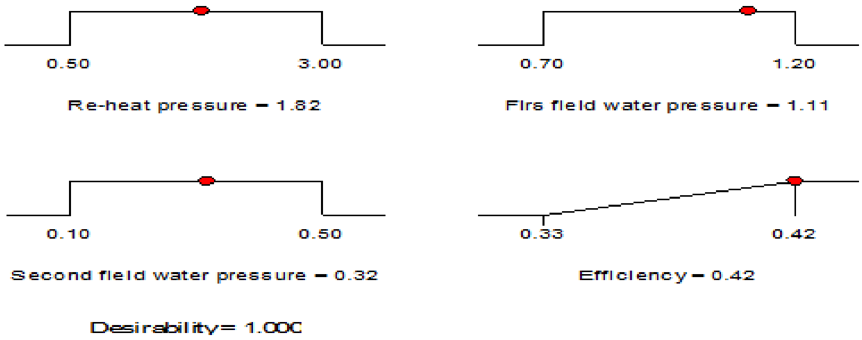

Figure 8: The optimal process conditions.

4.1 Validation experiments under optimum conditions

To investigate the optimized combinations, three experiments were conducted. The optimal value of input parameters is given in Table 3. Predicted efficiency is found to be in good agreement with the experimental value and the root mean square value of 0.0024 indicates the accuracy of the regression model. As a result, the model from response surface methodology was considreded to be accurate.

Table 3: Validation test results.

Experiment	RHP (MPa)	FFWP (MPa)	SFWP (MPa)	$^{1}\eta_p$ (%)	$^{2}\eta_e$ (%)
1	0.82	0.85	0.47	0.43	0.411
2					0.418
3					0.4182
				Mean	0.4157
				RMSE	0.0024

[1] Predicted efficiency [2] Experimental efficiency.

5.0 CONCLUSION

This work has demonstrated the application of the Box-behnken design in predicting optimum efficiency of a team plant which is a major performance parameter. For a proposed 10MW plant investigated in this study, the optimal solution of process condition obtained from three distinct operating parameters that were varied are: 0.82 MPa for re-heat pressure, 0.85 MPa for first feed pressure and 0.47 MPa for second field water pressure. These values gave the maximum value of steam turbine efficiency of 43% for the proposed steam plant. The validation test was conducted and the value of the root mean square was determined to be 0.0024.

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