PARAMETRIC DESIGN OPTIMIZATION OF SCISSOR LIFT PLATFORM – A DESIGN OF EXPERIMENT (DOE) APPROACH

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ABSTRACT

This paper illustrates a statistical approach for optimizing the parametric design and performance (e.g. height) of scissor lift elevators. Using dynamic model and kinematic analysis of scissor lift elevator, performance of the mechanism is simulated for different parametric combination to achieve certain height by the end effector or the platform. Simulation data are used to analyze the statistical significance of parameters on the performance of scissor lift mechanism using ANOVA technique. A two level fractional factorial design has been considered for the design optimization and it proved as a conductive approach for screening a large number of variables and reducing the no. of experiment to optimize the cost as well. For different level of parameters, optimum performances of the platform are compared and reported. Interactions between the parameter are analyzed and reported. Validation procedure has been tested and the design was proved to be scientific and reasonable and could serve as a reference for designing of scissor lifting mechanism.

Keywords: scissor lift; DOE; optimization.

CONCEPTION PARAMÉTRIQUE OPTIMISATION DE ÉLÉVATEUR À CISEAUX - UN PLAN D'EXPÉRIENCE (DOE) APPROCHE

RÉSUMÉ

Cet article illustre une approche statistique pour optimiser la conception paramétrique et de la performance (par exemple la hauteur) des ascenseurs élévatrices. En utilisant le modèle dynamique et l'analyse cinématique de ciseau ascenseur, la performance du mécanisme est simulé pour différentes combinaisons des paramètres pour faire certaine hauteur par l'effecteur d'extrémité ou la plate-forme. données de simulation sont utilisées pour analyser la signification statistique des paramètres sur la performance du mécanisme de levage à ciseaux selon une technique ANOVA. Un modèle factoriel fractionné à deux niveaux a été considéré pour l'optimisation de la conception et il se est avéré comme une approche de criblage d'un conducteur grand nombre de variables et de réduire le pas. d'expérience pour optimiser le coût ainsi. Pour le niveau de différents paramètres, les performances optimales de la plate-forme sont comparées et signalées. Interactions entre le paramètre sont analysées et présentées. Procédure de validation a été testé et la conception a été révélée être scientifique et raisonnable et pourrait servir de référence pour la conception des ciseaux mécanisme de levage.

Mots-clés : ciseau; DOE; optimisation.

1 INTRODUCTION

The scissor type elevating platforms are widely used for vertical transportation of load with or without human. This type of mechanism is the first choice for automobiles, assembly workers (e.g. engine parts assembly) and also for the maintenance workers at high altitude work. The mechanism can be mobile if it is mounted on the right vehicles [1]. Often this type of elevating platform dealing with high load and the mechanism needs to be very safe in terms of design as there are issues related with personal safety. Little success has been achieved for optimal design of the scissor lift mechanism due to difficult geometric constraints and complex model. *Liu et al*. in [2] proposed a simulative calculation based optimal design approach of scissor lift where the actuation principle is based on the hydraulic system. Usually the performances of the scissor lift elevators are tested in the laboratory which associated with huge cost and time. That’s why effective statistical analysis is a great addition for this type of mechanism. In our approach Fractional Factorial based design approach has been used for identifying the key factors involved with the scissor lift performance. Considered factors are varied according to the Dynamic and kinematic analysis. Responses are recorded from the simulation. Fractional factorial design approach involves the running of just a partial number of full factorial design and has a great advantage of identifying and isolating the significant factors with a minimum of experiments without neglecting the interaction effects between factors. Here for simulation and optimization data we considered a Bond Graph model of scissor lift mechanism proposed by *Islam et al*. [3]. They considered DC motor as driving mechanism and the whole mechanism is comprised of two very well-known mechanism (i.e. four bar and slider crank). According to their design the driving link is connected to the ground platform. Figure 1 show a two stage scissor lift mechanism based on DC motor driving link. The basic advantage of this design is that it doesn’t contain any prismatic actuator and the complexity is less compared to the hydraulic actuator. A brief review of the Design of Experiment (DOE) methodology is presented in the section 2. Experimental model is described in section 3. Simulation factors and response are described in section 4. Section 5 presents the simulation data, simulation outcome and detailed analysis of optimization procedure. Validation of the proposed method is tested in the section 6. Finally section 7 presents the concluding remarks.

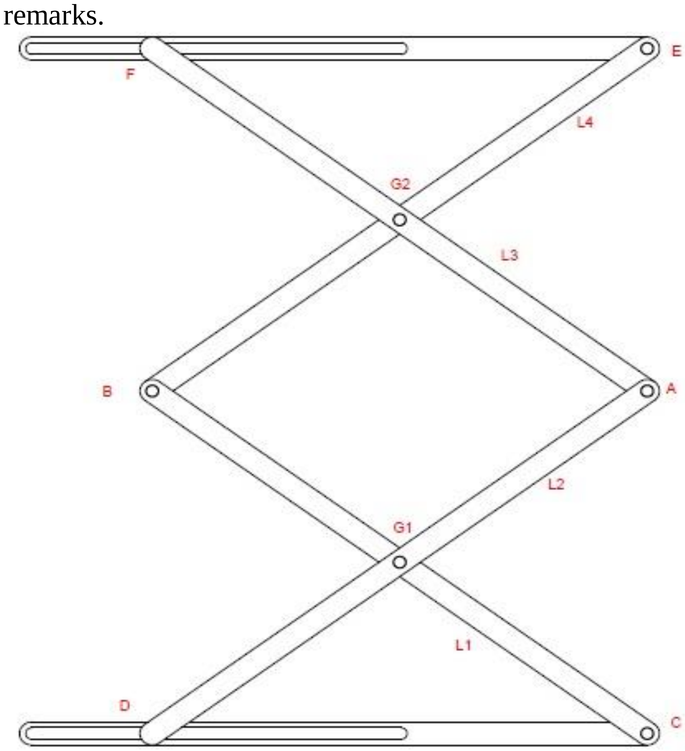

Fig. 1. Two stage scissor lift mechanism

2 DESIGN OF EXPERIMENT METHOD

Design of experiment is a test or a series of tests on which purposeful changes are made to the input variables or factors or a system so that we may observe and identify the reasons for changes in the output response(s). Initially there was no general method to reach optimal design except varying the parameters step by step and it is known as One Factor at A time (OFAT) method. But OFAT is not a valid approach when there are interactions between the parameters. The design of experiment (DOE) methodology started in the 1930 by R. A. Fisher [4]. Fisher and his co-workers used this technology to see different parameters impact on agricultural science and to reduce the experiments. Then the concept of ANOVA (Analysis of variance) was introduced. During the fifties and sixties Box and Wilson proposed response surface methodology which broaden the application of this methodology on the chemical and process industries. Then during seventies and eighties Taguchi proposed a robust parameter design approach [5]. His innovation's made the method popular in the business world. This approach widely used due to the introduction of computer technology. It's a structured and efficient procedure to plan experiments and to obtain data which can be analyzed for valid calculations about the studied products or process [6]. *Lahoud et al.*in [7] mentioned some advantages of DOE. In DOE we can learn about the investigating process and can screen out important variables. In addition of that the DOE analysis builds a mathematical model and gives provision for optimization run of the responses. The statistical significance of analysis is tested using ANOVA and the prediction model is obtained through the regression analysis. There are some important classes of factorial design. They are 2-level factorial design (2^K), Fractional Factorial Design (2^{K-P}) and Response Surface Methodology. When the number of factors becomes large enough to be interesting, the size of the design grows very quickly. Then fractional factorial design is the most efficient DOE approach. DOE can be used for a wide range of experiments for various purposes including nearly all fields of engineering. This approach provides opportunity to select design parameters so that the design will work under a wide variety of field conditions (robust design). DOE also used in mechanical engineering and in the robotics field. A DOE approach for the parametric design optimization of planar manipulator has been published in [8].

3 EXPERIMENTAL MODEL ANALYSIS

3.1 Kinematic Equations

Brief kinematic analysis of the two stage scissor lift mechanism is described in [3]. They considered *l* as the length of each link. For the design in Figure 2 the link length is equal for each link. Distance of the moving link from the fixed link is *S* and the midpoint height is *h*. Total height for one stage is, *H =2h*.

The height *h* with respect to the input angle *θ'* is:

$$h = \frac{l}{2}\sin\theta' \tag{1}$$

Height *h* in terms of input and output is:

$$h = \sqrt{\frac{l^2}{4} - \frac{S^2}{4}} \tag{2}$$

Velocity of the platform for one stage:

$$\frac{dH}{dt} = \left(\frac{1}{\sqrt{\frac{l^2}{4} - \frac{S^2}{4}}}\right)\left(\frac{l}{2}\frac{dl}{dt} - \frac{S}{2}\frac{dS}{dt}\right) \tag{3}$$

Acceleration of the end effector is:

$$\frac{d^2H}{dt^2} = \left(-\frac{1}{2}\right)\left(\frac{1}{\left(\frac{l^2}{4} - \frac{S^2}{4}\right)^{\frac{3}{2}}}\right)\left(\frac{l}{2}\frac{dl}{dt} - \frac{S}{2}\frac{dS}{dt}\right)^2 + \left(\frac{1}{2}\right)\left(\frac{1}{\sqrt{\frac{l^2}{4} - \frac{S^2}{4}}}\right)\left[\left(\frac{dl}{dt}\right)^2 + l\frac{d^2l}{dt^2} - \left(\frac{dS}{dt}\right)^2 + S\frac{d^2S}{dt^2}\right] \tag{4}$$

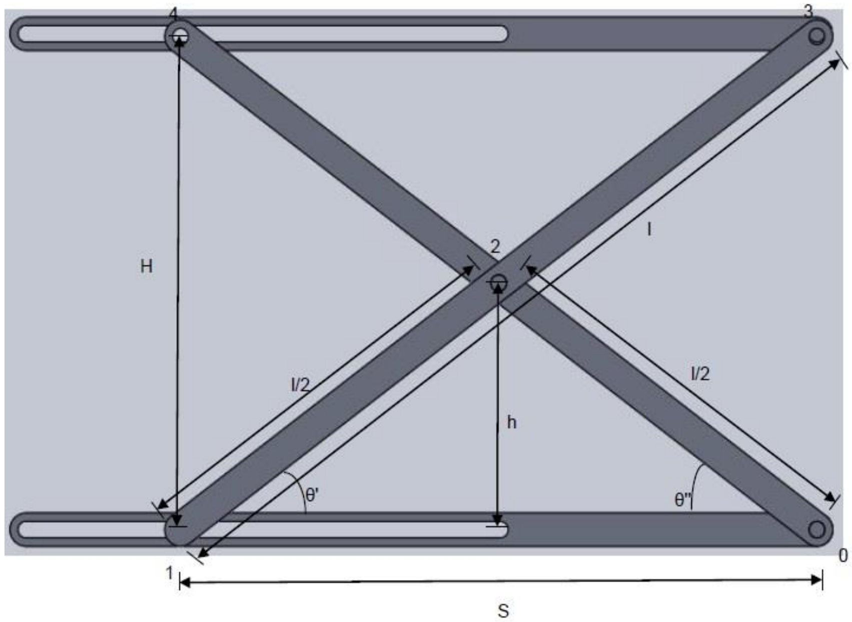

Fig. 2. Kinematic Analysis Figure

3.2 Dynamic Model Analysis

A detailed bond graph model for dynamic analysis of the mechanism is presented in [3]. That paper describes every single component modeling of the mechanism. From that modeling concept 20-sim software has been used to get the simulation data. Figure 3 shows the BG model for simulation. Parasitic stiffness and damping is considered to do the joint modeling and they considered as the global parameter. Vector bond has been used to represent the nonmoving portion. To make a link nonmoving or static zero effort source has been used. Centre of mass points between the links are connected and the platform is also connected according to the design. A simple PID controller has been used and the parameters of the controller are described in the original model of that paper.

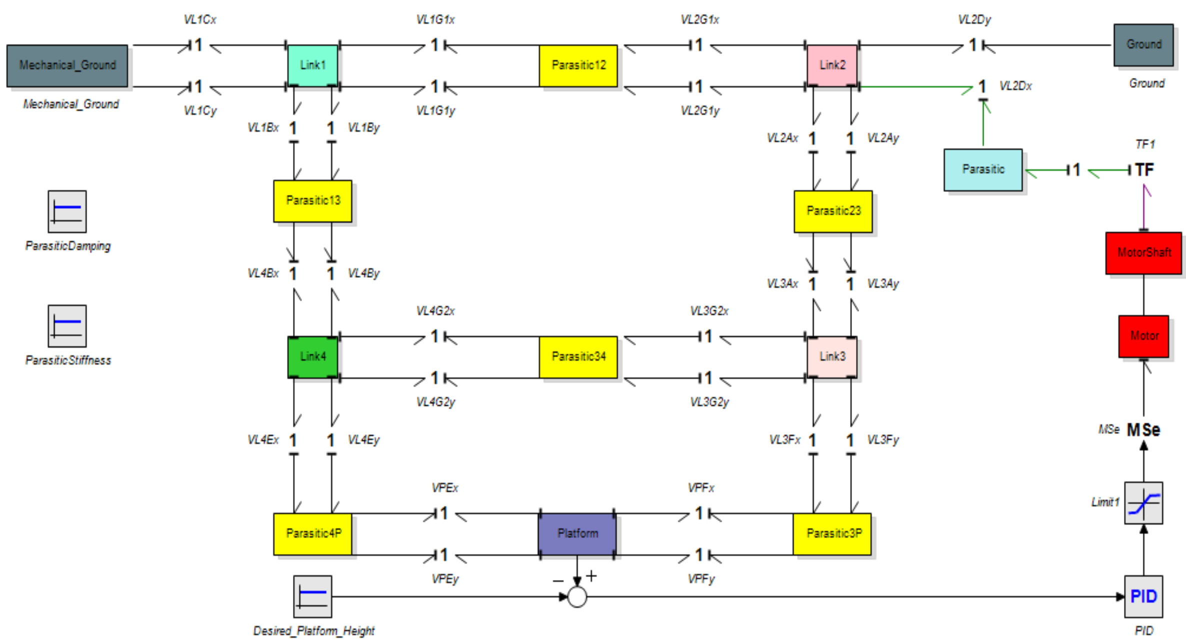

Fig. 3. Bond Graph Model for Simulation

4 EXPERIMENTAL FACTORS AND RESPONSE

Various parameters influencing the performance of scissor lift are identified based on their kinetic and dynamic analysis. Here we considered five parameters as input factors and the output response is the height of the platform.

Mass of Each Link (A): Scissor lift mechanism is the combination of extended four bar and slider crank. Each of the links has an effect on its performance. In the experiment, link mass is allowed to have two different levels. We considered link mass – 3 lbs (low level) and link mass– 5 lbs (high level).

Link Length (B): If the length of the link increases then it will increase the height coverage of the scissor lift elevator. But on the other hand mass will also increase. The DC motor needs to supply more torque. Considered two different link lengths are 6 in (low level) and 8 in (high level).

Platform Load (C): There is a platform on the top of the scissor lift elevator to carry human or other load. This load is another vital factor for scissor lift type elevator. The main purpose of the mechanism is to lift load to a certain height. Platform load combines the mass of the platform as well as the carrying load. Here in this design the chosen platform loads are 15 lbs (low level) and 25 lbs (high level).

Motor Torque (D): Based on the supplied motor torque the structure will move vertically. When the mass of the system or load increases then the motor needs to supply more input torque. The considered two levels are 20 in_lbs (low level) and 30 in_lbs (high level).

Repetition of Stages (E): The main structure of a scissor lift elevator consists of several extended rhombus structure repetitions. Rhombus structure is made with 4 links of equal mass and equal length [9]. Two links connected in their center of mass form a stage. To increase the number of stages two center connected links needs to be connected with two other center on mass connected link. Increase in the number of stages will cause increase in the height performance of the elevator. But increase of stages will also cause increase in weight and requires more torque to lift the same load up to certain height. Here we consider 2 stage repetition as low level and 3 stage repetition as high level.

The response is the platform height lifted by the scissor lift. For different level of the considered five factors the response (height) was recorded from the simulation. For five factors, a full factorial design needs a total of $2^5 = 32$ runs. Instead we use a half fractional factorial design with a total of $2^{5-1} = 16$ runs. One effect has to be confounded and we choose I = ABCDE as the confounding effect. As this is a resolution V design, all the main effects and two factor interactions can be estimated clearly. Three factor interactions are aliased with two factor interactions. But they are not significant and can be ignored. The experiment was carried out with the standard run order for fractional factorial design. The factors were arrayed with the specified run order and every time the associated factor values were changed according to the design summary. The model was run by the 20 sim software and output values were measured from the simulation data file.

5 DOE MODEL ANALYSIS

5.1 Fractional Factorial Design of the Experiment

A 2^{5-1} fractional factorial requiring 16 runs was designed to determine the influence of the five factors and interactions of factors. Design Expert software (version 8.0.6) by Stat-Ease was used to develop a design of Resolution V. An alias structure automatically chosen by the software takes the advantage of the sparsity of effects - that is, high order interactions are aliased with main and two factor interactions. Figure 4 shows the alias structure of the design produced by Design-Expert with the run order and the data. Figure 5 shows the effect list and their interaction effects. From the effect list we can also determine the positive or negative impact of the factors on the performance.

5.2 Analysis of Experimental Data

While analyzing the data, the most important factors and their interaction effects are considered. Figure 4 and Figure 5 shows the effect of A, B, C, D, E and the interaction of CD and DE are the main contributors as there percentage contributions are very high. Remaining factors have no significant contributions to height performance as there percentage contributions are less than 1.

Select	Std	Run	Factor 1 A:Mass of Each Link lbs	Factor 2 B:Link Length in	Factor 3 C:Platform Load lbs	Factor 4 D:Motor Torque in_lbs	Factor 5 E:Repitition of Stages	Response 1 Height in
	1	2	-1.00	-1.00	-1.00	-1.00	1.00	39.8
	2	1	1.00	-1.00	-1.00	-1.00	-1.00	31.2
	3	11	-1.00	1.00	-1.00	-1.00	-1.00	33
	4	9	1.00	1.00	-1.00	-1.00	1.00	32.1
	5	3	-1.00	-1.00	1.00	-1.00	-1.00	26.8
	6	16	1.00	-1.00	1.00	-1.00	1.00	27.4
	7	15	-1.00	1.00	1.00	-1.00	1.00	28
	8	5	1.00	1.00	1.00	-1.00	-1.00	22
	9	6	-1.00	-1.00	-1.00	1.00	-1.00	35.8
	10	7	1.00	-1.00	-1.00	1.00	1.00	46.5
	11	4	-1.00	1.00	-1.00	1.00	1.00	47.3
	12	13	1.00	1.00	-1.00	1.00	-1.00	33.6
	13	12	-1.00	-1.00	1.00	1.00	1.00	46.8
	14	14	1.00	-1.00	1.00	1.00	-1.00	34.5
	15	10	-1.00	1.00	1.00	1.00	-1.00	35.3
	16	8	1.00	1.00	1.00	1.00	1.00	41

5 Factors: A, B, C, D, E

Design Matrix Evaluation for Factorial 2FI Model

Factorial Effects Aliases

[Est. Terms] Aliased Terms

[Intercept] = Intercept
[A] = A
[B] = B
[C] = C
[D] = D
[E] = E
[AB] = AB + CDE
[AC] = AC + BDE
[AD] = AD + BCE
[AE] = AE + BCD
[BC] = BC + ADE
[BD] = BD + ACE
[BE] = BE + ACD
[CD] = CD + ABE
[CE] = CE + ABD
[DE] = DE + ABC

Fig. 4. Aliased terms including run list and Data for Experiment

Term	Stdized Effects	Sum of Squares	% Contribution
A-Mass of Each Link	-3.06	37.52	4.39
B-Link Length	-2.06	17.02	1.99
C-Platform Load	-4.69	87.89	10.29
D-Motor Torque	10.06	405.02	47.40
E-Repitition of Stages	7.09	200.93	23.51
AB	-0.66	1.76	0.21
AC	0.063	0.016	1.828E-003
AD	0.66	1.76	0.21
AE	-0.66	1.76	0.21
BC	-0.24	0.23	0.026
BD	0.46	0.86	0.10
BE	-0.96	3.71	0.43
CD	3.29	43.23	5.06
CE	-0.94	3.52	0.41
DE	3.51	49.35	5.78
ABC		Aliased	
ABD		Aliased	
ABE		Aliased	
ACD		Aliased	
ACE		Aliased	
ADE		Aliased	
BCD		Aliased	
BCE		Aliased	
BDE		Aliased	
CDE		Aliased	
ABCD		Aliased	
ABCE		Aliased	
ABDE		Aliased	
ACDE		Aliased	
BCDE		Aliased	
ABCDE		Aliased	

Fig. 5. Effect List

5.3 Pareto Chart and Half Normal Plot

From the pareto chart bar graph we can screen out the most significant factors and their interaction effects. There is a cutoff point line to compare significance of the effects. Figure 6 shows that from our considered parameters all of the parameters single factor effects are significant. Interactions between DE and CD are the most dominant two interactions. Figure 7 shows the half normal plot and it justifies the same result for the effects. The most significant factors will be away from the line in the half normal plot.

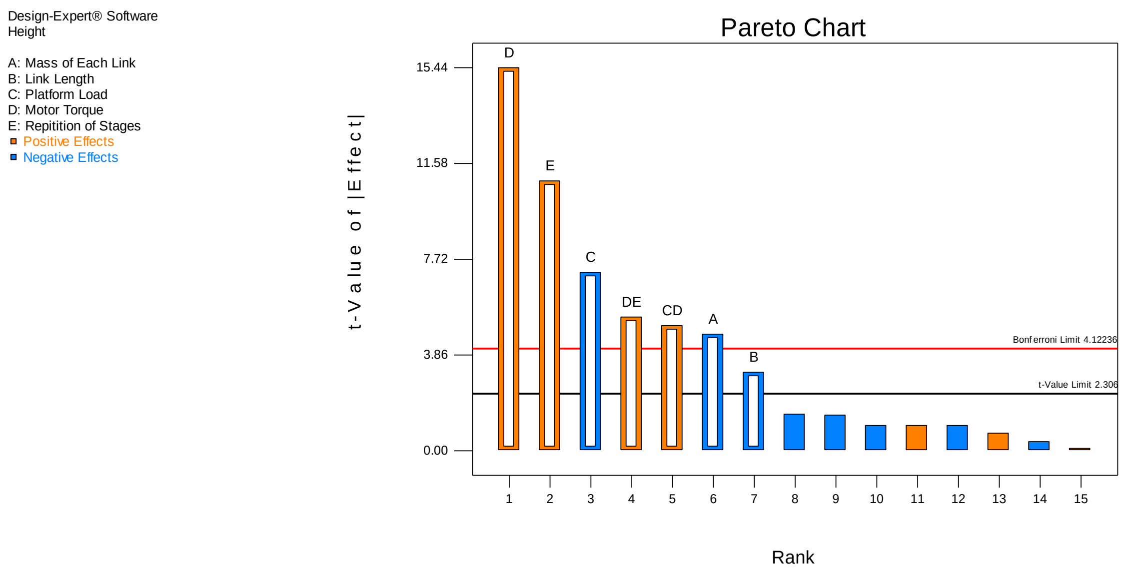

Fig. 6. Pareto Chart

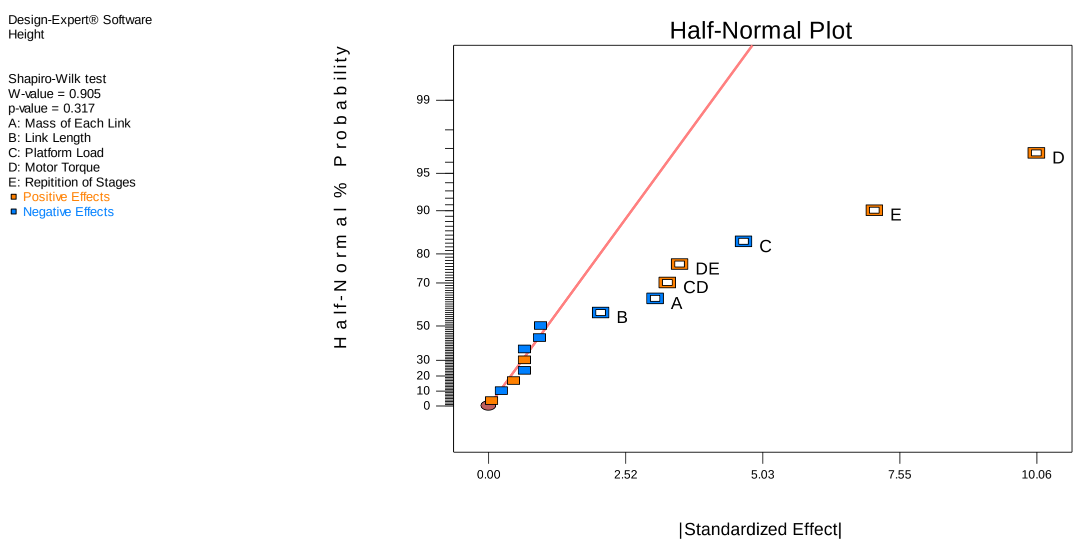

Fig. 7. Half Normal Plot

5.4 ANOVA Analysis and Regression Model

The ANOVA table summarizes the significance. From the F-value and probability value comparison of the effects, the software concludes the significance. In summary the standard shows the deviation of the error term. R^2 presents the percentage of total variability explained by the model. Addition of effect will increase the R value. That's why we should look at the adjusted R value produced by the model. The difference between the two R^2 should be very small. Precision should be greater than 4 for an adequate model. Figure 8 shows the ANOVA table and the ANOVA summary for the proposed model. The R^2 values are very close and precision is much greater than 4 which signify the adequacy of the model. Figure 9 represents a mathematical model for the output response of the scissor lift.

5.5 Residual Analysis

Residual analysis checks whether the assumptions of the ANOVA are correct or not. We made following assumptions:

1. Random Samples from their respective population.
2. All samples are independent.
3. Departures from group mean are normally distributed for all data groups.
4. All data groups have equal variance.

Use your mouse to right click on individual cells for definitions.

Response 1 Height

ANOVA for selected factorial model

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	840.95	7	120.14	70.75	< 0.0001	significant
A-Mass of Ea	*37.52*	*1*	*37.52*	*22.09*	*0.0015*	
B-Link Lengt	*17.02*	*1*	*17.02*	*10.02*	*0.0133*	
C-Platform L	*87.89*	*1*	*87.89*	*51.76*	*< 0.0001*	
D-Motor Torq	*405.02*	*1*	*405.02*	*238.51*	*< 0.0001*	
E-Repitition c	*200.93*	*1*	*200.93*	*118.32*	*< 0.0001*	
CD	*43.23*	*1*	*43.23*	*25.46*	*0.0010*	
DE	*49.35*	*1*	*49.35*	*29.06*	*0.0007*	
Residual	13.59	8	1.70			
Cor Total	854.53	15				

Std. Dev.	1.30	R-Squared	0.9841
Mean	35.07	Adj R-Squared	0.9702
C.V. %	3.72	Pred R-Square	0.9364
PRESS	54.34	Adeq Precisior	27.742

The "Pred R-Squared" of 0.9364 is in reasonable agreement with the "Adj R-Squared" of 0.9702.

"Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 27.742 indicates an adequate signal. This model can be used to navigate the design space.

Fig. 8. ANOVA table with the summary

Final Equation in Terms of Coded Factors:

Height =
+35.07
-1.53 * A
-1.03 * B
-2.34 * C
+5.03 * D
+3.54 * E
+1.64 * C * D
+1.76 * D * E

Final Equation in Terms of Actual Factors:

Height =
+35.06875
-1.53125 * Mass of Each Link
-1.03125 * Link Length
-2.34375 * Platform Load
+5.03125 * Motor Torque
+3.54375 * Repitition of Stages
+1.64375 * Platform Load * Motor Torque
+1.75625 * Motor Torque * Repitition of Stages

Fig. 9. Regression Model

From the normal probability plot (Figure 10) it is obvious that maximum points follow a straight line. So the distributions of residuals are almost normal. The plot of Residuals vs. Predicted (Figure 11) looks like well scattered which indicates constant variance. Figure 12 shows the Residuals vs Run plot. From the plot we can see most of the data are random i.e. no trend and points are beyond the red line. The Predicted vs. Actual plot (Figure 13) shows that points are randomly scattered along the 45 degree line. Groups of points above or below the line indicate areas of over or under prediction. Finally from the Box-Cox plot of Figure 14 we can see that the current line (blue line) is between the ranges (between Low & High Confidence Interval). This recommends for no transformation. So, we can conclude that the assumptions of ANOVA are satisfied.

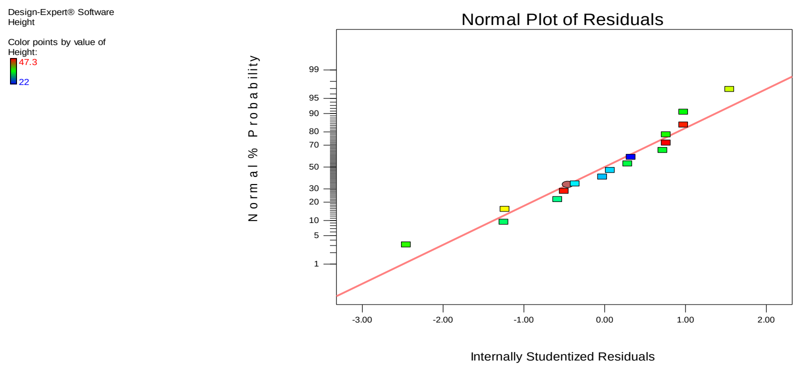

Fig. 10. Normal Plot

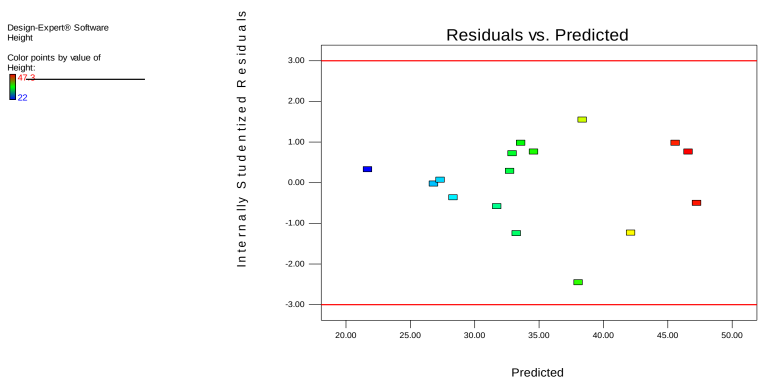

Fig. 11. Residuals vs. Predicted Plot

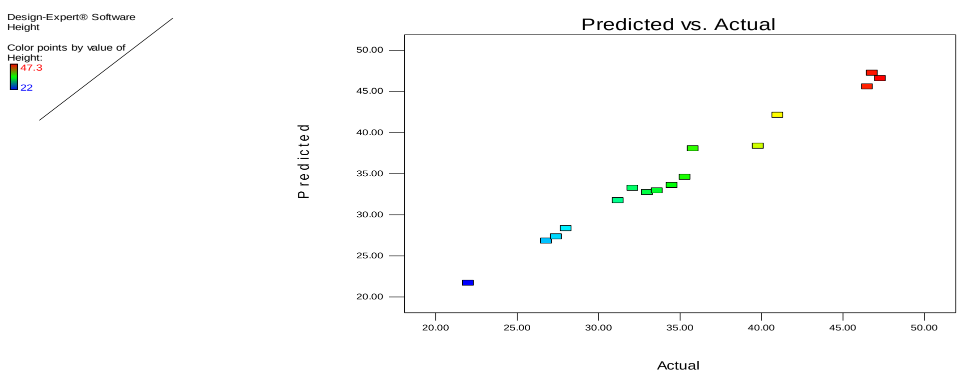

Fig. 12. Predicted vs. Actual plot

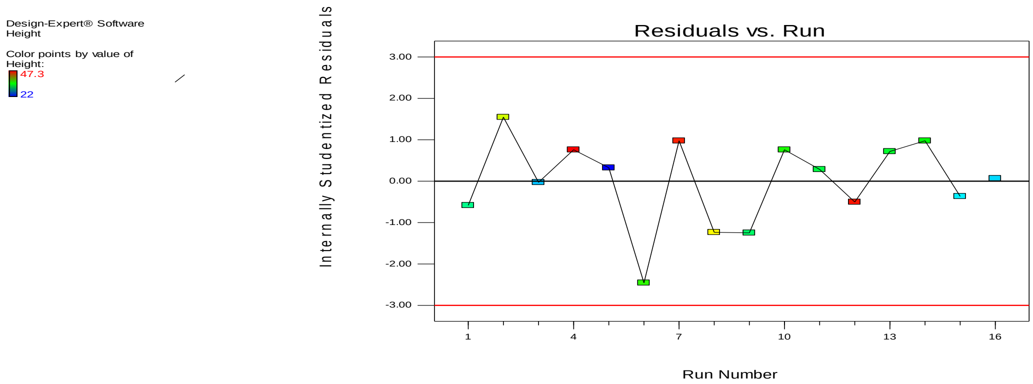

Fig. 13. Residuals vs. run Plot

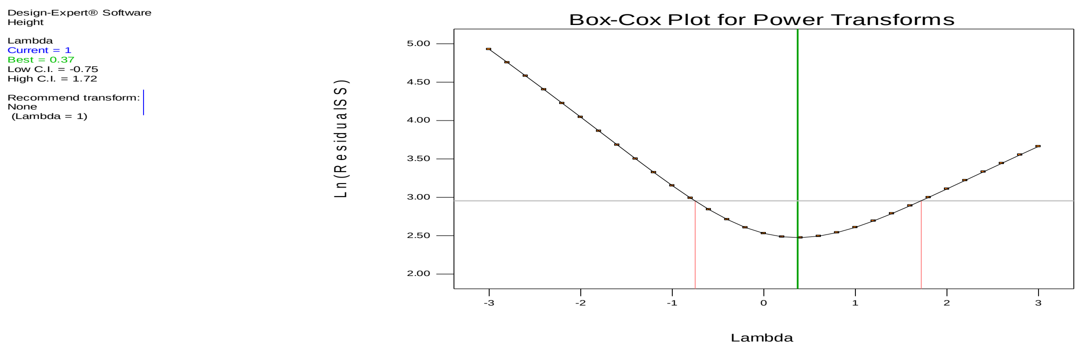

Fig. 14. Box-cox plot for power transformation

5.6 Interactions

From the interactions graph we can determine the effect of the parameters on the response. Figure 15 shows the single factor effect on the height performance for two factors. We can see that both factor A and B has negative effect on performance. As we move from low to high level, performance decreasing slightly. Parameter B has more detrimental effect than A. In the same way the other three factors interactions can be described. Figure 16 shows the two factor interaction curve of the CD and DE. It indicates that the height performance will reduce with the increase of C from low level to high level for both level of D. For low level the reduction is more rapid compared to the high level. On the other hand if we increase the factor D from low to high level the performance will increase for both level of E. High level of E has more positive effect compared to the low level. For both case interactions effect becomes smaller as we move from low to high. Figure 17 shows the outcome of model optimization run.

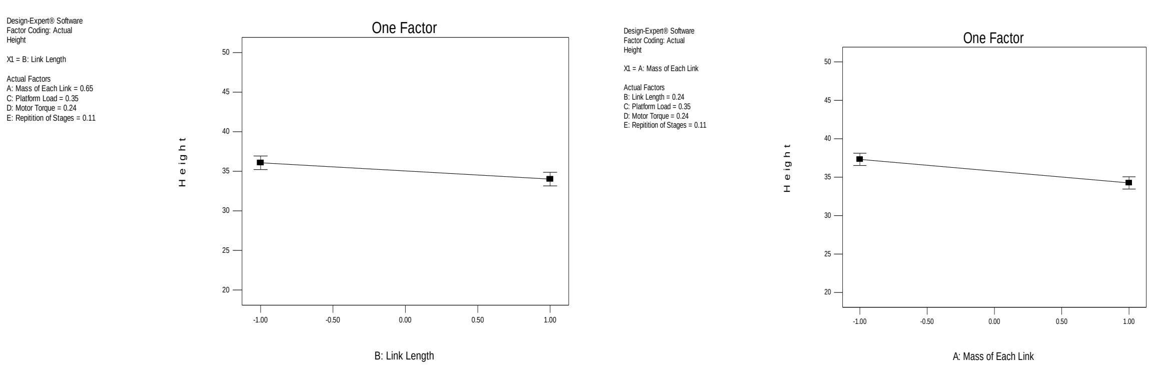

Fig. 15. Single Factor Interaction Graph

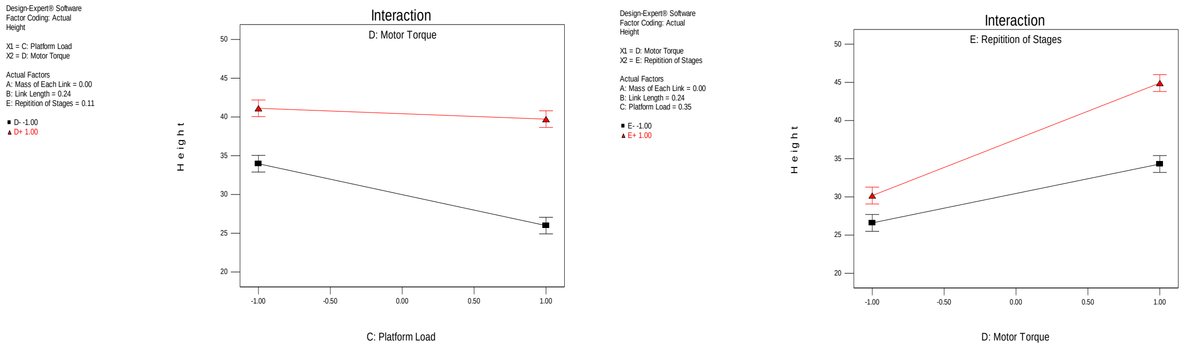

Fig. 16. Two factors interaction

Name	Goal	Limit	Limit	Weight	Weight	Importance
A:Mass of Eac	is in range	-1	1	1	1	3
B:Link Length	is in range	-1	1	1	1	3
C:Platform Loa	is in range	-1	1	1	1	3
D:Motor Torqu	is in range	-1	1	1	1	3
E:Repitition of :	is in range	-1	1	1	1	3
Height	is target = 40	22	47.3	1	1	3

Solutions

Number	Mass of Each	Link Length	Platform Load	Motor Torque	Repitition of Stages	Height	Desirability	
1	0.69	-0.68	0.54	0.63	0.60	40.0001	1.000	Selected
2	-0.98	-0.98	-0.99	-0.66	0.98	40.0001	1.000	
3	0.96	0.76	-0.92	0.96	0.32	40	1.000	
4	-0.97	-0.97	-0.98	0.98	-0.61	40	1.000	
5	-0.93	0.96	0.82	0.98	0.04	40	1.000	
6	-0.59	0.82	-0.64	0.20	0.66	40	1.000	
7	-0.52	-0.39	0.79	0.67	0.28	40	1.000	
8	0.96	-0.92	0.78	0.98	0.20	40.0001	1.000	
9	0.98	0.99	0.99	0.77	0.95	40	1.000	
10	0.93	-0.93	-0.90	0.61	0.24	40	1.000	

Fig. 17. Optimization Runs for validation

6 MODEL OPTIMIZATION

The model was optimized and extra runs performed for validity check. All factors were kept in range and the platform height was fixed at 40 in to get the optimum runs. First ten combinations were verified and the output obtained was fair enough to describe the model as a valid one. Figure 16 shows that for the certain height all factors are in their specified range and we can determine the values for each of the factor. Output confirms the validity of the model to find the parametric combination and their respected values for certain height coverage. Here factor values are given in their coded form.

7 CONCLUSION

A fractional factorial design has been performed to investigate the significance of the major effects and their interaction. The detailed study shows the effect of major five factors (A,B,C,D and E) and the interaction of CD and DE is most dominant. The motor torque and repetition of rhombus stages was the most significant contributor for scissor lift height output. The model has a very good R-squared value of 98.4% which signifies the models suitability. Moreover additional validation runs were performed that they match the optimization scheme. The model was actually made and simulated by using the 20 sim tool. It's very reliable to describe the dynamic modeling of the system with the help of bond graph. For design optimization of scissor lift type elevating platform using the DOE methodology and fractional factorial design one can reduce the number of experiment and make the study more cost effective where result will be almost as accurate as laboratory set up. Hence the DOE methodology can be an efficient estimate of designing the scissor lift elevator. The DC motor based scissor elevator can also be used as linear actuator for parallel manipulator.

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