International Journal of Power Control Signal and Computation (IJPCSC)
Vol. 5. No.1. pp.37-55,Jan-March 2013 ISSN: 0976-268X
www.ijcns.com

Statistical Modeling Approach for Optimization of a Pneumatic Reciprocating Step Feeder

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Abstract

The work aims at the optimization of the output feed rate of a Pneumatic Reciprocating Step Feeder so that the best possible set of parameters affecting it can be selected to get the desired output. For this purpose the effect of various parameters on the feeder output is studied. To facilitate the study and detailed analysis, a statistical model is constructed which is used to predict and optimize the performance of the system. Efficient feed rate optimization determines the input variable settings to adjust the feed rate of the feeder according to the consumption of the parts in the next phase of production. A physical model of pneumatic reciprocating step feeder was fabricated. In this system, cylindrical parts from the buffer are carried through the steps of the feeder to be delivered in proper quantity and orientation. The factors influencing the feeder's performance include part population, number of strokes per minute and length of the parts to be fed. A series of experiments is performed on the three process parameters to investigate their effect on the feed rate. To study the interaction among the factors a full 2^3 factorial experiment approach has been adopted using the two basic principles of experimental design- replication and randomization. The process model was formulated based on Analysis of variance (ANOVA) using Design-Expert® statistical package. The outcome is represented graphically and in the form of empirical model which defines the performance characteristics of the Pneumatic Reciprocating Step Feeder.

Keywords- Pneumatic Reciprocating Step feeder, Feed rate optimization, Full 2^3 factorial design, ANOVA.

I. INTRODUCTION

An assembly line is an arrangement of workers, machines, and equipment in which the product being assembled passes consecutively from operation to operation until completed. [1]

In automated assembly systems, part feeders play a very important role as they are responsible for supplying the machine continuously segregated parts at a specific flow rate and orientation. In such automated feeder systems part flow rate is of primary importance as the orientation in most of the cases can be controlled easily. The feed rate should not fall below machine rate which leads to a condition of starvation. Feeders form a critical part of automated assembly lines. Along with feeding from a bulk supply, they also convert the randomness of parts into a flow in a geometrical pattern and deliver them at a predetermined rate.

The present work aims at fabricating, experimenting and investigating a pneumatic reciprocating step feeder. The system has been designed in such a way that the experimental observations can be easily used to generate the parameters at which the feeder's performance is optimum.

II. GENERAL REQUIREMENTS

The following are some of the general considerations that must be followed while designing a part feeder:

1. A point that must be borne in mind when considering part feeders is that in mechanized assembly, the output of parts from the feeder is always restricted by the machine being fed. The machine will generally use parts at a strictly uniform rate and this may be referred to as the machine rate. In the design and testing of the part feeders it is often convenient to observe the feed rate when the feeder is not connected to a machine i.e. when no restriction is applied to the output of the feeder. The feed rate under these circumstances is referred to as the unrestricted feed rate. The unrestricted feed rate should be greater than the machine rate.
2. With part feeders suitable for automatic machines it is necessary that all the parts be presented to the machine in the same orientation. Some feeders are able to feed and orient many types of parts whilst others are only able to handle a very limited range of part shapes.
3. A part feeder should be reliable i.e. it should be designed so that the possibility of parts jamming in the feeder is minimized or eliminated.
4. Some part feeders are noisy in operation and some tend to damage certain types of parts.

These aspects must be considered when studying the possible alternatives for a particular application.

III. CLASSIFICATION OF FEEDERS

Part feeders can be classified as [2]:

1) Reciprocating block feeder
2) Rotary disk feeders
3) Stationary hook feeder
4) Paddle wheel feeder
5) Hook feeder
6) Reciprocating tube feeder
7) Reciprocating fork feeder
8) Rotary centreboard feeder
9) External gate feeder
10) Magnetic disk feeder
11) Centrifugal tube revolving hook feeder

Usually vibratory bowl feeders are used for feeding most of the basic part shapes. But sometimes they are incapable of feeding parts of a particular shape and thus we have selected the Non-Vibratory reciprocating block feeders for analysis.

IV. PRINCIPLE OF WORKING

The basic principle of working of a pneumatic reciprocating step feeder is the relative motion between the stationary box and the reciprocating step. [3] The set up is designed such that cylindrical parts are fed to their respective desired positions. In this set up there is a bulk storage box that acts as a temporary reservoir for the randomly stored parts to be fed whenever the device is operational. This box has tapered edges to avoid the formation of dead zones. Tapered sides facilitate the parts to the centre of the box, where a reciprocating step, swings up and down through the storage area. The steps are such that two of them are fixed and three for m the reciprocating step assembly. The fixed steps are integral to the stationary box and inclined to the vertical wall of box so as to facilitate the transfer of parts from one step to another. The reciprocating step assembly moves between the fixed steps such that first and second step are equal in height to the first and second fixed step respectively so that when the step moves up, parts slide to the next step. The top step has been provided a suitable taper to facilitate the sliding of the parts from it to the desired position. The stroke length of the actuator is equal to the height of first step. When the step moves down, it picks up parts from the storage area and on moving up; it transfers the part to the next step of equal height. In the next down stroke, the third step is at a height lower than the second one. So the parts roll onto the next step and when the step moves up again, they roll to the fixed step of equal height. After another up and down stroke, the parts slide down the topmost step to the desired position. The reciprocating process goes on and specific numbers of parts are delivered at a rate decided by many factors like part population, reciprocation speed and part size. In this feeder, the feed rate is higher as compared to single step feeder. Also the probability of starvation of the machine is lower.

Table1. Specifications

S. No.	PART NAME	SPECIFICATIONS
1.	Stationary Box	Length: 16 in Breadth: 16 in Height: 7 in
2.	Reciprocating Step	Length: 5 in Breadth: 5 in 1^{st} step height: 5 in 2^{nd} step height: 7.5 in 3^{rd} step height: 10 in 3^{rd} step taper: 1 85
3.	Pneumatic Actuator	Bore dia: 24 mm Stroke length: 120 mm
4.	Solenoid Valve	5/4 direction control valve DC 24 V

Figure1.Experimental setup

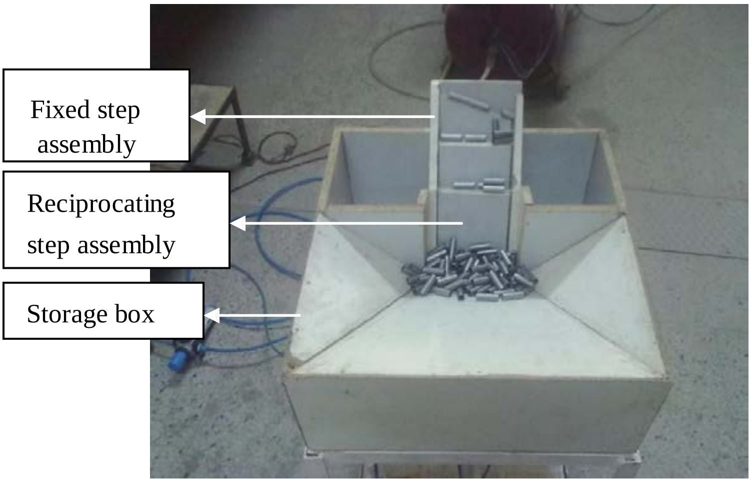

Figure2.Parts of the feeder

V. DRIVING MECHANISM

The reciprocating driving mechanism to the step in this feeder is given by a pneumatic system.

The pneumatic system consists of a double acting pneumatic actuator, 5/4 solenoid valve, timer, pressure gauge, pipes and compressor. The pressure gauge controls the pressure supplied to the actuator which is kept at 3.2 bars. The flow control valves on the actuator are used to vary the flow of compressed air in the actuator, thus controlling the intensity of the stroke of reciprocating step. A timer connected between the pressure gauge and valve is used to set the number of strokes per minute. Compressed air from the compressor, kept constant at 3.2 bar by the pressure gauge flows into the 5/4 solenoid valve and is used to operate the actuator. The actuator reciprocates under the action of the valve. The pneumatic components of the system are as shown in figure 3.

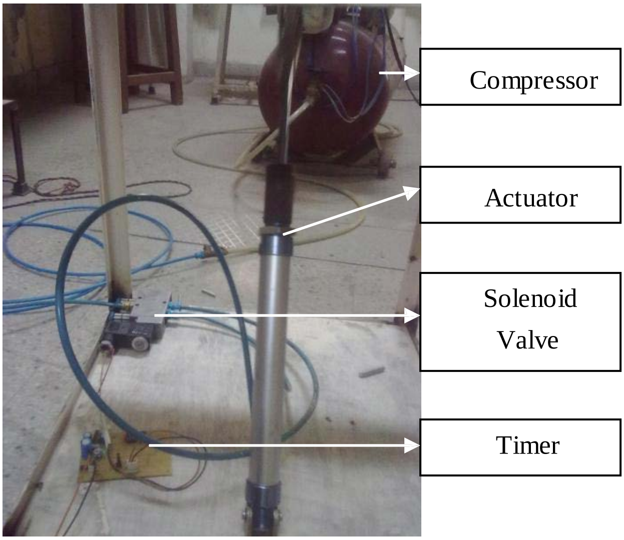

Figure3. Driving Mechanism

VI. EXPERIMENTAL WORK

In the present work, an investigation is done for the performance of the reciprocating feeder used in automatic production for feeding. The project primarily aimed at fabrication and analysis of results for the feeder. [4]

Also, a series of experiments are carried out under different operating conditions. Analysis has been done to study the effect of three parameters: ***a) Part population***

b) Part size

c) Number of strokes of reciprocating step

However other parameters like step angle and slope of the box in which parts are placed can also be experimented to find their influence on feed rate.

VI. RANGES OF PARAMETERS

a) Population of parts *in the feeder*: Part population is varied from 50 to 450.

b) Part dimensions: The parts are cylindrical with the following dimensions:

1) Diameter=6.2mm, Length=25mm
2) Diameter=6.2mm, Length=30mm
3) Diameter=6.2mm, Length=35mm

c) Speed of the reciprocating block**:** The speed or strokes/min of the block varies from a minimum of 10 strokes per minute to 50 strokes per minute.

VIII. FACTORIAL APPROACH

The purpose of the experimentation is to establish a statistical model to predict the output feed rate and its successful optimization using 2^k factorial design. The three factors chosen for experiment are the controllable variables that have a key role to play in the process characterization. These design factors have a certain range within which they can be varied for the useful functioning of the system. The ranges of individual factors were chosen on the basis of pilot runs and process knowledge based on practical experience [5]. The upper and lower bounds of the range of each factor, which were coded as +1 and -1, are given in the Table 2.

Table2. Process parameters

Process parameters	Low level (-1)	High level (+1)
Part population (A)	50	450
Strokes/min (B)	10	50
Part length(mm) (C)	25	35

Since we have three factors to be considered, the experiment design is called a 2^3 full factorial design which required eight test runs, each with combinations of the three factors across two levels of each. According to the general statistical approach for experimental design three replicates were
obtained to get a reliable and precise estimate of the effects. Therefore, twenty four observations were taken in all to employ full factorial design as shown in Table 3.Throughout the experiment it was assumed that: the factor is fixed, the design was completely randomized and the usual normality assumptions of the data were satisfied.

Table3. Experimental data

RUNS	CODED FACTORS			FEED RATE (parts/min)		
	A	B	C	R1	R2	R3
1	+1	+1	+1	141	148	140
2	+1	+1	-1	190	190	196
3	+1	-1	+1	47	52	50
4	+1	-1	-1	51	57	50
5	-1	+1	+1	67	70	72
6	-1	+1	-1	70	83	75
7	-1	-1	+1	18	18	16
8	-1	-1	-1	30	25	29

IX. ANALYSIS

DesignExpert® is an excellent statistical package that assists in data analysis. Various plots like Cube plot, Interaction plot and One factor plot are obtained to examine effects of factors on output. Pareto plot and Normal plot of the standardized effects are obtained to compare the significance of each effect. Analysis of Variance (ANOVA) table is constructed for the significant factors affecting the output response.

9.1 Effect of factors on feed rate

The cube plot for feed rate (Figure 4) shows the average feed rates at critical points. The critical points are those points where all the parameters have limiting values. We gather that a minimum feed rate of 17.333 parts per minute can be achieved for which we need to select minimum part population and minimum rpm for the maximum part size. The maximum achievable feed rate is 193.333 parts per minute at maximum rpm, maximum part population, and with minimum part size.

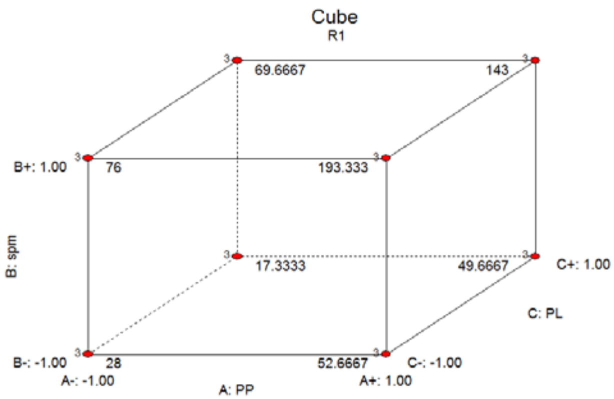

Figure4. Cube Plot

Figure 5, 6 and 7 depict a plot of average output for each level of two factors with the level of third factor held constant. These plots called interaction plots are used to interpret significant interactions between the process parameters. Interaction is present when the response at a factor level depends upon the levels of other factors. Since they can magnify or diminish the main effects of the parameters, evaluating interactions is extremely important.

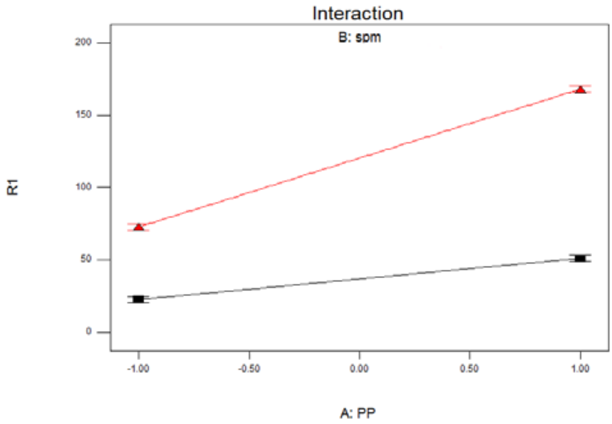

Figure5. Interaction plot between Part Population (A) and Speed (B)

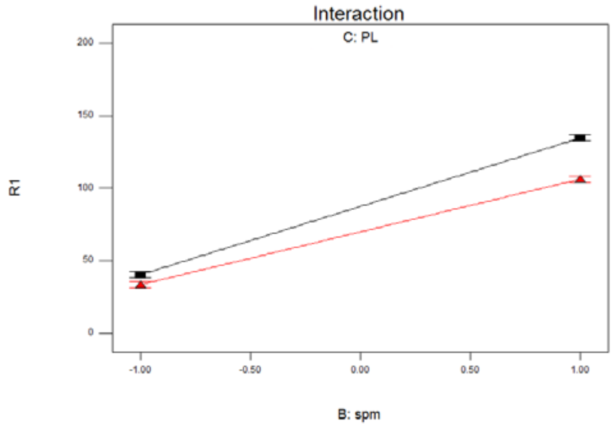

Figure6. Interaction plot between Speed (B) and Part Length(C)

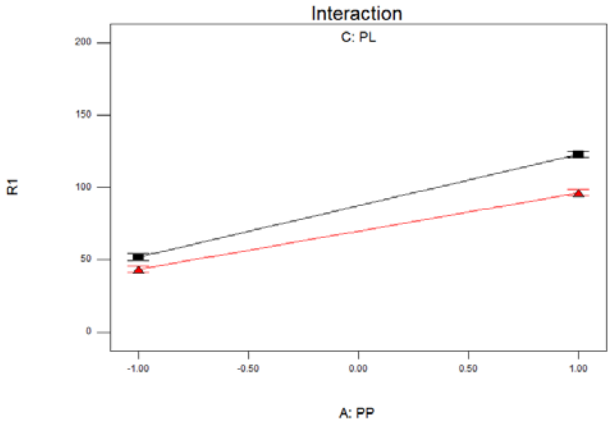

Figure7. Interaction plot between Part Population (A) and Part Length(C)

All three interaction plots depict synergic interaction between the concerned factors in each graph. Although the lines on the plot do not cross each other but lack of parallelism of the lines exhibit significant interaction. The greater the departure of the lines from the parallel state, the higher the degree of interaction.[6]

It is also important to know how the system behaves when variation is brought upon by varying only one parameter keeping the others constant. This gives the dependence of the system over the varied parameter. A main effect occurs when the mean response changes across the levels of a factor. The one factor graphs (Figure 8, 9, 10) can be used to compare the relative strength of the effects across factors. It can be asserted from the graph that the speed and part population have positive effects while the part size has negative effect on the output feed rate. It can also be concluded that SPM has profound effect on the output followed by part size and part population.

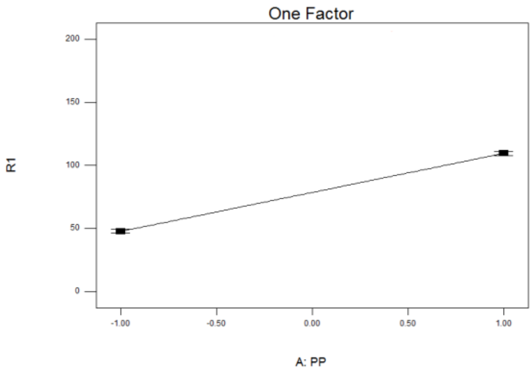

Figure8. Effect of Part Population (A) on Feed Rate (R1)

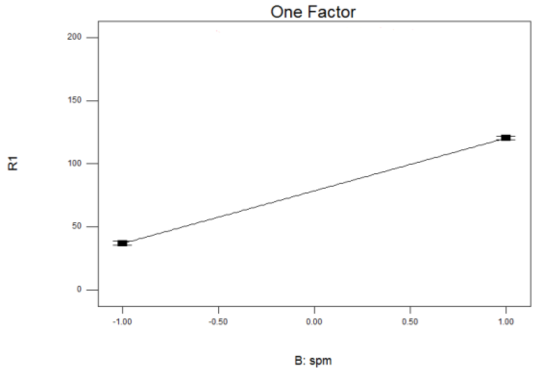

Figure9. Effect of Speed (B) on Feed Rate (R1)

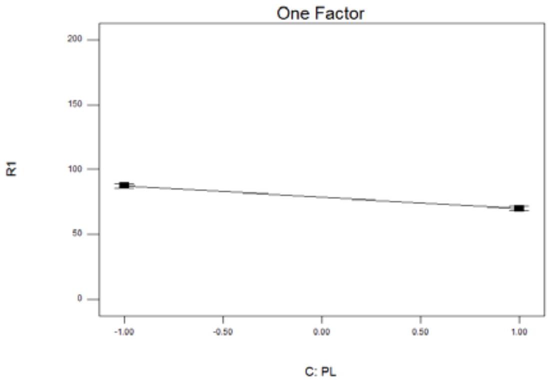

Figure10. Effect of Part Length (C) on Feed Rate (R1)

9.2 Significance of various factors

The Pareto Chart of the Effects (Figure 11) and the Normal Plot of Standardized Effects (Figure 12) also assist to determine the magnitude and the importance of an effect. Pareto chart displays the absolute value of the effects and draws a reference line on the chart at t-value limit, where t is the (1 - α/2) quantile of a t-distribution with degrees of freedom equal to the degrees of freedom (16) for the error term. Any effect that extends within this reference line is statistically insignificant. The effect of B has the highest standardized effect on the feed rate followed by A, AB, C, ABC, BC and AC. However all effects extend above the t-value limit, hence significant. The significance of all factors can be reasserted from the normal plot, in which, the points that do not fall near the fitted line are important. The factors having negligible effect on the output response tend to be smaller and are centered on zero.

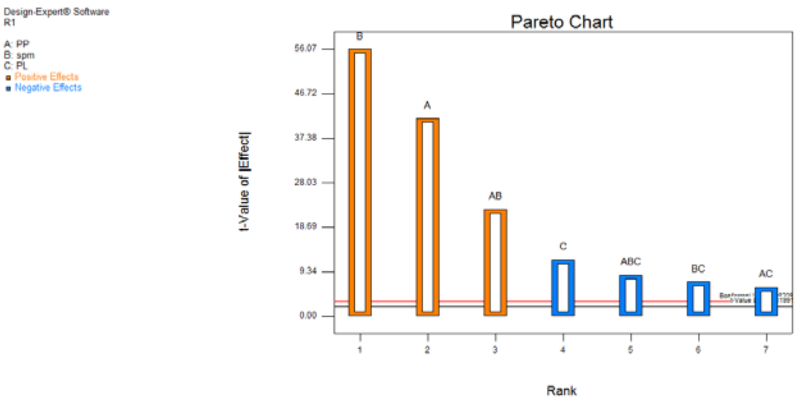

Figure11. Pareto chart

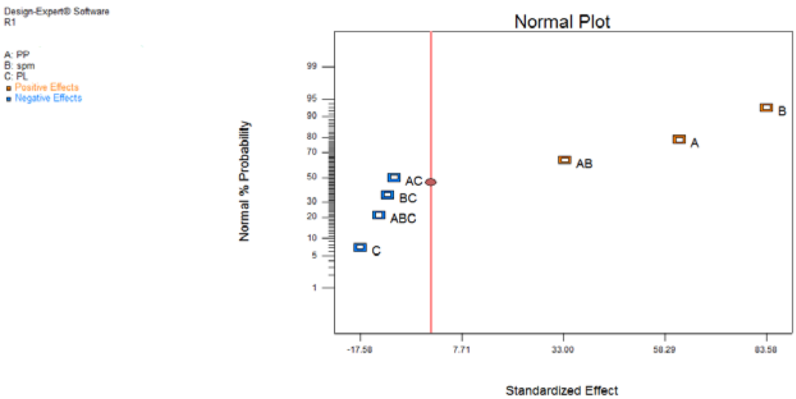

Figure12. Normal plot of standardized effects

9.3 Development and significance of model

Considering all the parameters to be significant, The final outcome as given by Designexpert® software after incorporating these changes is given below.

Final equation in terms of actual factors:

Feed Rate=

+78.70833
+30.95833 * Part Population
+41.79167 * SPM
-8.79167 * Part Length

+16.70833 * Part Population * SPM
-4.54167 * Part Population *Part Length
-5.37500 * SPM * Part Length
-6.45833 * Part Population * SPM * Part Length

The F Value for a term is the test for comparing the variance associated with that term with the residual variance. It is the Mean Square for the term divided by the Mean Square for the Residual. P value is the probability value that is associated with the F Value for this term. It is the probability of getting an F Value of this size if the term did not have an effect on the response. In general, a term that has a probability value less than 0.05 would be considered a significant effect. A probability value greater than 0.10 is generally regarded as not significant.

- ☐ The Model F-value of 810.68 implies the model is significant. (Table 4) There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. Values of "Prob. > F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, BC, ABC are significant model terms.

Table4. Analysis of variance table [Partial sum of squares - Type III]

Source	**Sum of Squares**	**Df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	75663.63	7	10809.09	810.68	< 0.0001
A-Part Population	23002.04	1	23002.04	1725.15	< 0.0001
B-SPM	41917.04	1	41917.04	3143.78	< 0.0001
C-Part Length	1855.04	1	1855.04	139.13	< 0.0001
AB	6700.04	1	6700.04	502.50	< 0.0001
AC	495.04	1	495.04	37.13	< 0.0001
BC	693.38	1	693.38	52.00	< 0.0001
ABC	1001.04	1	1001.04	75.08	< 0.0001
Pure Error	213.33	16	13.33		
Cor total	75876.96	23			

Table5. Predicted vs Actual values

Standard Order	Actual Value	Predicted Value	Residual
1	29.00	28.00	1.00
2	25.00	28.00	-3.00
3	30.00	28.00	2.00
4	50.00	52.67	-2.67
5	57.00	52.67	4.33

Standard Order	Actual Value	Predicted Value	Residual
6	51.00	52.67	-1.67
7	83.00	76.00	7.00
8	70.00	76.00	-6.00
9	75.00	76.00	-1.00
10	190.00	193.33	-3.33
11	194.00	193.33	0.67
12	196.00	193.33	2.67
13	16.00	17.33	-1.33
14	18.00	17.33	0.67
15	18.00	17.33	0.67
16	52.00	49.67	2.33
17	50.00	49.67	0.33
18	47.00	49.67	-2.67
19	67.00	69.67	-2.67
20	70.00	69.67	0.33
21	72.00	69.67	2.33
22	148.00	143.00	5.00
23	140.00	143.00	-3.00
24	141.00	143.00	-2.00

Table6. Diagnostics Case Statics

Std. Dev.	3.65	**R-Squared**	0.9972
Mean	78.71	**Adj R-Squared**	0.9960
C.V. %	4.64	**Pred R-Square**	0.9937
PRESS	480.00	**Adeq Precision**	83.484

- R square measures the proportion of total variability explained by the model. From Table 5 the value of R squared is 0.9972. A potential problem with this statistic is that it always increases as factors are added to the model even if these factors are not significant. So the adjusted R squared was calculated which was 0.9960.
- The prediction error sum of squares statistic is a measure of how well the model will predict new data. The value of PRESS for our model was 480.00 (Table 5). The value for predicted R squared is 0.9927. This indicates that the full model would be expected to explain about
  99.27% of the variability in new data.
- "Adeq Precision" measures the signal to noise ratio. A ratio greater
  than 4 is desirable. Hence a ratio of 83.484 (Table 5) indicates an adequate signal. This model can be used to navigate the design space.
- The mathematical equation for the feed rate was obtained for the actual factors. The Diagnostics Case Statistics (Table 6) compares the actual and predicted values and obtains the residual.

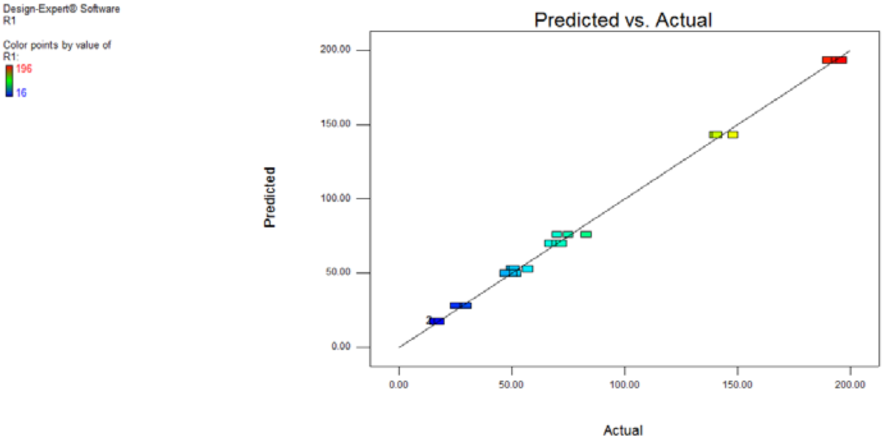

Figure13. Predicted vs. Actual graph

9.3 Optimization of Feedrate

This equation can be used to find out the values of the three factors to be set in order to achieve desired output feed rate. The optimization procedure picks several starting points from which search for the optimal factor settings is begun. There are two types of solutions for the search:

Local solution: For each starting point, there is a local solution. These solutions are the combination of factor settings found beginning from a particular starting point.

Global solution: There is only one global solution, which is the best of all the local solutions. The global solution is the "best" combination of factor settings for achieving the desired responses.

For each of the local solution, predicted value of the response is calculated. The desirability of each of the predicted values asses its closeness to the target value on a scale of 0 to 1. A reduced gradient algorithm with multiple starting points is employed to maximize the desirability in order to determine the numerical optimal or the global solution.

Solutions found for the constraints in Table 7 are shown in Table 8. The selected solution is the global solution.

Table7. Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:PP	is in range	-1	1	1	1	3
B:spm	maximize	-1	1	1	1	3
C:PL	is in range	-1	1	1	1	3
R1	maximize	16	196	1	1	3

Table 8 Solutions

Number	Part Population (A)	SPM (B)	Part Length (C)	Feed Rate (R1)	Desirability
1	1.000	1.000	-1.000	193.333	0.993 Selected
2	0.989	1.000	-1.000	192.7	0.991
3	1.000	0.991	-1.000	192.709	0.989
4	0.972	1.000	-1.000	191.672	0.988
5	1.000	1.000	-0.924	191.415	0.987
6	1.000	1.000	-0.899	190.788	0.985
7	1.000	0.990	-0.922	190.693	0.983
8	0.938	1.000	-0.961	188.728	0.980
9	1.000	1.000	-0.816	188.703	0.980
10	1.000	0.962	-0.987	190.313	0.975

Number	Part Population (A)	SPM (B)	Part Length (C)	Feed Rate (R1)	Desirability
11	1.000	0.957	-1.000	190.3	0.973
12	0.866	1.000	-1.000	185.461	0.970
13	1.000	1.000	-0.510	181.006	0.957
14	1.000	1.000	-0.436	179.14	0.952
15	1.000	1.000	-0.226	173.861	0.936
16	1.000	0.999	-0.129	171.348	0.929
17	1.000	1.000	0.027	167.497	0.917
18	1.000	1.000	0.056	166.756	0.915
19	1.000	1.000	0.190	163.392	0.905
20	1.000	1.000	0.380	158.601	0.890
21	1.000	1.000	0.482	156.042	0.882
22	0.222	1.000	-1.000	147.67	0.855
23	0.865	1.000	1.000	138.037	0.823
24	0.692	1.000	1.000	131.696	0.802
25	0.426	1.000	1.000	121.937	0.767
26	0.379	1.000	1.000	120.248	0.761
27	-0.264	1.000	0.493	102.369	0.693

In an exemplary situation, a feed rate of 170 parts per minute for the parts of size 30mm (coded as 0) is to be targeted and corresponding optimum values of the remaining two factors need to be found. The results obtained from optimization are shown below in Table 10.

Table9.
Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:PP	is in range	-1	1	1	1	3
B:spm	maximize	-1	1	1	1	3
C:PL	is equal to 0	-1	1	1	1	3
R1	is target=170	16	196	1	1	3

Table10. Solutions

Number	PP	spm	PL	R1	Desirability
1	1.000	1.000	0.000	168.167	0.994 (Selected)
2	0.887	1.000	0.000	162.768	0.976
3	0.741	1.000	0.000	155.819	0.953

X. CONCLUSION

A reliable statistical model based on full factorial experiment design has been developed which can be used for the optimization of output feed rate of the stationary hook hopper feeder. The model is significant to explain 99% of variability in new data. Such a model not only assists to estimate the magnitude and direction of the effects of change in factors but also predicts the effects of their mutual interactions.

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