CASE 54

Linear Proportional Purge Solenoids

Abstract: The purpose of an evaporative emission control system is to control fuel vapors that accumulate in a gas tank and carbon canisters. Due to strict Environmental Protection Agency regulations on the control of fuel vapor and to customer requirements, the need for a new technology became apparent. This new solenoid offers a better continuous proportional flow with a high degree of flow controllability. To eliminate the sensitivity of the current design on all forms of variation, this design was selected for robust engineering methods. Using math-based models, the subfunctions were improved from 30 to 60%. This study shows that decomposition of the functional block diagram is a powerful tool in the design process using computer simulation model in the early stage of concept development.

1. Introduction

The principal components of an evaporative emissions control system are a carbon canister, tank pressure transducer, rollover orifice, liquid separator, and the purge solenoid, a valve that functions to meter fuel vapor from the fuel tank and a carbon canister to the intake manifold (Figure 1). The linear proportional purge solenoid project was initiated to develop a linear purge solenoid that offers a continuous proportional flow with a high degree of flow controllability.

This particular solenoid design proposes to meet or exceed the existing flow and noise specification and has the potential to replace or compete with comparable products currently in use in the marketplace.

2. Problem Statement

The objective of using robust engineering methods in the design of the linear proportional purge solenoid was to reduce part-to-part flow and opening point variation and to minimize the effects of the following sources of variability: (1) environment (temperature, atmospheric pressure), (2) materials variation, (3) manufacturing and assembly variation, and (4) operating conditions (vacuum).

3. Objectives and Approach to Optimization

The objective of the study was to optimize the design through a validated simulation model. The success factors assigned to the optimization process were as follows:

1. *Proportional purge flow.* The flow is controlled by a current level that is maintained using a high-frequency pulse-width-modulated (PWM) signal (Figure 2). Flow is proportional to the percentage of duty cycle at the PWM signal (Figure 3). A current driver controlling the solenoid is needed.
2. *Vacuum independent flow.* Under operating conditions, the vacuum effect on the flow has to be minimized.

 Taguchi's Quality Engineering Handbook. Genichi Taguchi, Subir Chowdhury and Yuin Wu

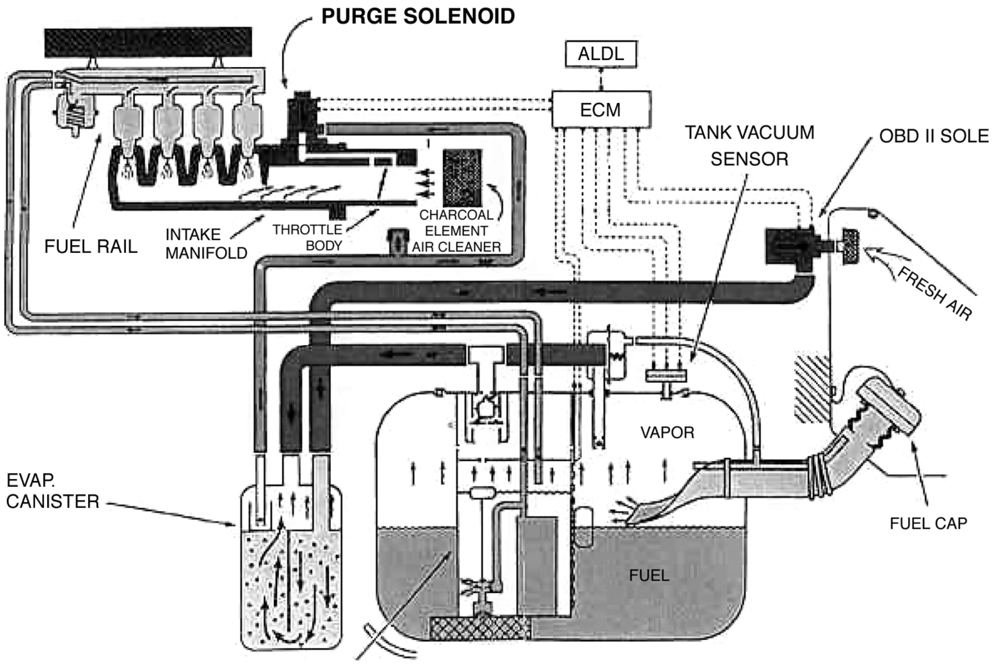


Figure 1
System hardware

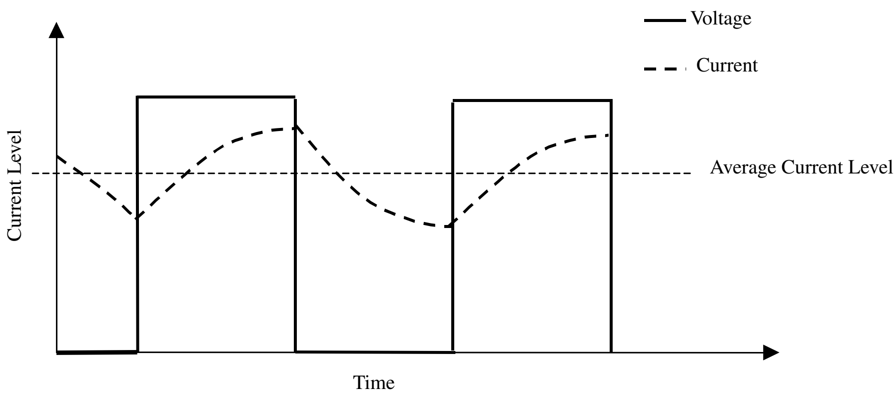


Figure 2
Current level maintained using high-frequency PWM signal

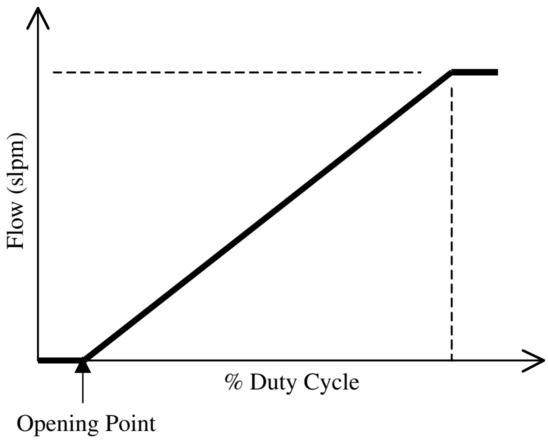


Figure 3
Linear proportional flow

3. *Opening point stability.* The solenoid has to control the flow of fuel vapor at a low duty cycle percentage.
4. *Low part-to-part variation.* Reduction of part-to-part variation of flow and opening point is required.

To achieve such proportional behavior of flow, it was necessary that the energy conversion be controlled on each of the three functions of the solenoid.

4. Simulation Models

Every subsystem was optimized using a specific simulator for each case. For the magnetic package, Ansoft Maxwell was used, solving an axisimetric finite-element model of the magnetic circuit. Ansoft Maxwell simulators are currently used and have been validated in the past. The error estimate for Ansoft Maxwell is about 1.5%, based on comparing other models to actual test data.

For a spring package, a mathematical model was developed. The general equation for a spring-mass-forced system is

$$m\ddot{x} + c\dot{\chi} + kx = F(t) \tag{1}$$

where m is the mass, c the damping coefficient, k the spring constant, and F the excitation force. From the definition of a linear proportional purge solenoid, the magnetic force is not a function of the travel; therefore, the deexcitation force is not a

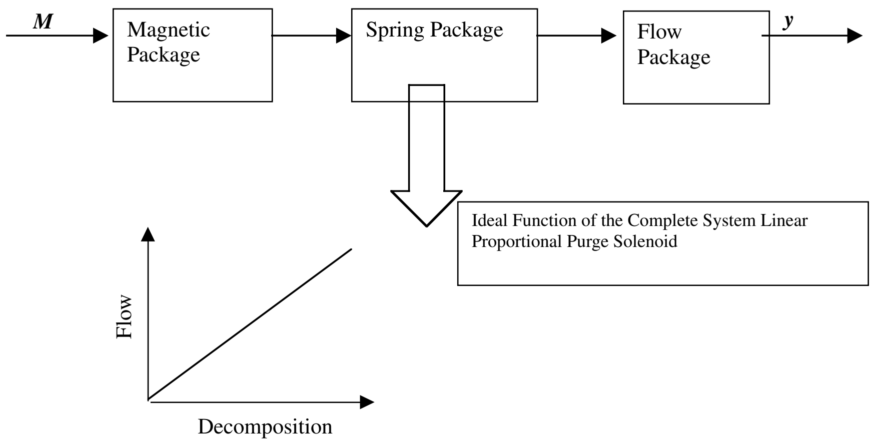


Figure 4
Functional decomposition into three subsystems

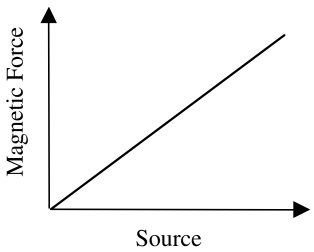


Figure 5
Ideal function

Magnetic package: force is proportional to the number of amp-turns (source)

function of the travel. The solution was obtained using the numerical method of finite differences.

The Taylor series for the position is given as

$$X_{i+1} = x_i + \frac{dx}{dt}\Delta t + \frac{d^2x}{dt^2}\frac{\Delta t^2}{2} + \cdots + \frac{d^nx}{dx^n}\frac{(\Delta x)^n}{n!} \tag{2}$$

Table 1
Control factors and levels[a]

Factor	Level 1	2	3
A	Low[a]	Average	High
B	Low	Average[a]	High
C	Low	Average[a]	High
D	Low	Average[a]	High
E	1	2	3[a]
F	1	2	3[a]
G	1	2	3[a]
H	1	2	3[a]
I	Low[a]	Average	High
J	Low	Average[a]	High
K	Low	Average[a]	High
L	Low	Average[a]	High
M	Low	Average[a]	High

[a] Current design level.

$$X_{i-1} = x_i - \frac{dx}{dt}\Delta t + \frac{d^2x}{dt^2}\frac{\Delta t^2}{2} + \cdots + (-1)^n\frac{d^nx}{dx^n}\frac{(\Delta x)^n}{n!} \tag{3}$$

Equations (2) and (3) can be written as

$$\frac{dx}{dt} = \frac{x_{i+1} - x_i}{\Delta t} \tag{4}$$

$$\frac{d^2x}{dt^2} = \frac{x_{i+1} - 2x_i + x_{i-1}}{\Delta t^2} \tag{5}$$

Placing equations (4) and (5) in equation (1), the position (through the time) is given as

$$x_{i+1} = \frac{F + (2x_i - x_{i-1})(m/\Delta t^2) + (c/\Delta t)\ x_i}{m/\Delta t^2 + c/\Delta t + k} \tag{6}$$

For the flow package, Star CD was used, solving an axial finite-element model of the pneumatic valve. Star CD simulator is currently used and has been validated in the past. The numerical error estimated from the solver is around 3%.

5. Functional Decomposition

To control the energy conversion of the solenoid, the design optimization process was made using functional decomposition. The study focused on three different packages or subsystems. The three subsystems were optimized separately. They were connected linearly (Figure 4) to complete an ideal function of the system level of the solenoid. Each engineered system uses energy transformation to

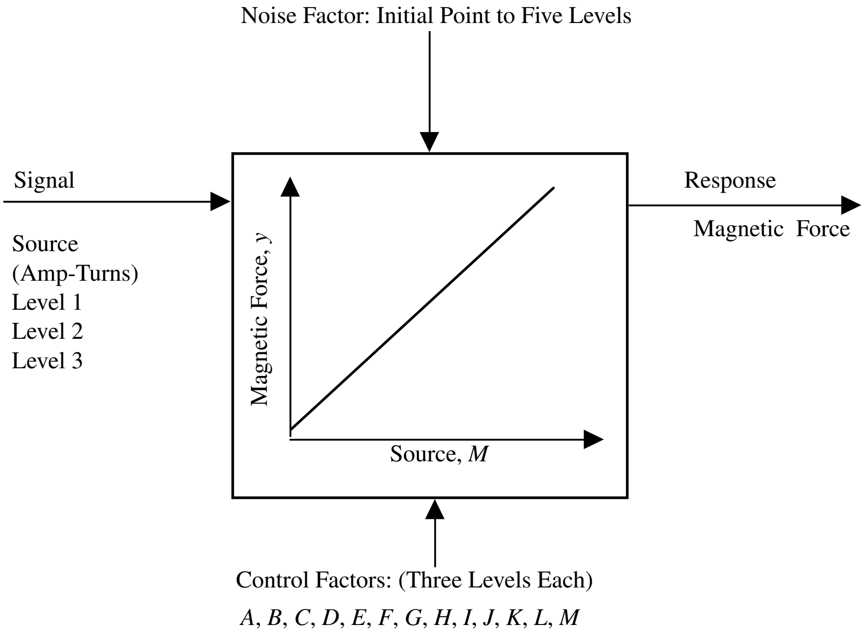


Figure 6
Parameter design

convert input energy into specific output energy and they are connected linearly (dynamic function).

6. Parameter Design

Ideal Function for the Magnetic Package

The function of a magnetic package is to provide a magnetic force to the plunger movement. For this package the input signal is an average electrical current level that is controlled by the percent of the duty cycle and the frequency (high-frequency PWM signal).

The design of the magnetic package for the linear proportional solenoid was based on (1) the magnitude of the magnetic force being proportional to the source (amp-turns), and (2) the magnetic force being independent of the position of the plunger.

According to the two points mentioned above, the ideal function for this package is as shown in Figure 5.

The first robust design experiment to be studied is the magnetic force (newtons) out of the magnetic package.

Signal and Noise Strategies Three levels of source (amp-turns) were selected (Table 1). These values represent the complete range of the electrical current under operation conditions. The initial point or position of the plunger was treated as a noise because the magnetic force should obtain its linear behavior insensitive to the effects of the travel setting, and the magnitude of the magnetic force is independent of the plunger position. Five levels of the initial point were selected.

The parameter diagram, illustrating the relationship of the control factors, noise factors, signal factor, and the response to the subsystem of the

Table 2
Experiment layout

														Signals and Initial Points																
	Control Factor													1					2					3						
No.	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***	***J***	***K***	***L***	***M***	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**SN**	**β**
1	1	1	1	1	1	1	1	1	1	1	1	1	1																	
2	2	2	2	2	2	2	2	2	2	2	2	2	1																	
3	3	3	3	3	3	3	3	3	3	3	3	3	1																	
4	1	1	1	1	2	2	2	2	3	3	3	3	1																	
5	2	2	2	2	3	3	3	3	1	1	1	1	1																	
6	3	3	3	3	1	1	1	1	2	2	2	2	1																	
7	1	1	2	3	1	2	3	3	1	2	2	3	1																	
8	2	2	3	1	2	3	1	1	2	3	3	1	1																	
9	3	3	1	2	3	1	2	2	3	1	1	2	1																	
10	1	1	3	2	1	3	2	3	2	1	3	2	1																	
11	2	2	1	3	2	1	3	1	3	2	1	3	1																	
12	3	3	2	1	3	2	1	2	1	3	2	1	1																	
13	1	2	3	1	3	2	1	3	3	2	1	2	2																	
14	2	3	1	2	1	3	2	1	1	3	2	3	2																	
15	3	1	2	3	2	1	3	2	2	1	3	1	2																	
16	1	2	3	2	1	1	3	2	3	3	2	1	2																	
17	2	3	1	3	2	2	1	3	1	1	3	2	2																	
18	3	1	2	1	3	3	2	1	2	2	1	3	2																	
19	1	2	1	3	3	3	1	2	2	1	2	3	2																	

Table 2
(*Continued*)

	Control Factor													Signals and Initial Points																
														1					2					3						
No.	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***	***J***	***K***	***L***	***M***	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**SN**	**β**
20	2	3	2	1	1	1	2	3	3	2	3	1	2																	
21	3	1	3	2	2	2	3	1	1	3	1	2	2																	
22	1	2	2	3	3	1	2	1	1	3	3	2	2																	
23	2	3	3	1	1	2	3	2	2	1	1	3	2																	
24	3	1	1	2	2	3	1	3	3	2	2	1	2																	
25	1	3	2	1	2	3	3	1	3	1	2	2	3																	
26	2	1	3	2	3	1	1	2	1	2	3	3	3																	
27	3	2	1	3	1	2	2	3	2	3	1	1	3																	
28	1	3	2	2	2	1	1	3	2	3	1	3	3																	
29	2	1	3	3	3	2	2	1	3	1	2	1	3																	
30	3	2	1	1	1	3	3	2	1	2	3	2	3																	
31	1	3	3	3	2	3	2	2	1	2	1	1	3																	
32	2	1	1	1	3	1	3	3	2	3	2	2	3																	
33	3	2	2	2	1	2	1	1	3	1	3	3	3																	
34	1	3	1	2	3	2	3	1	2	2	3	1	3																	
35	2	1	2	3	1	3	1	2	3	3	1	2	3																	
36	3	2	3	1	2	1	2	3	1	1	2	3	3																	

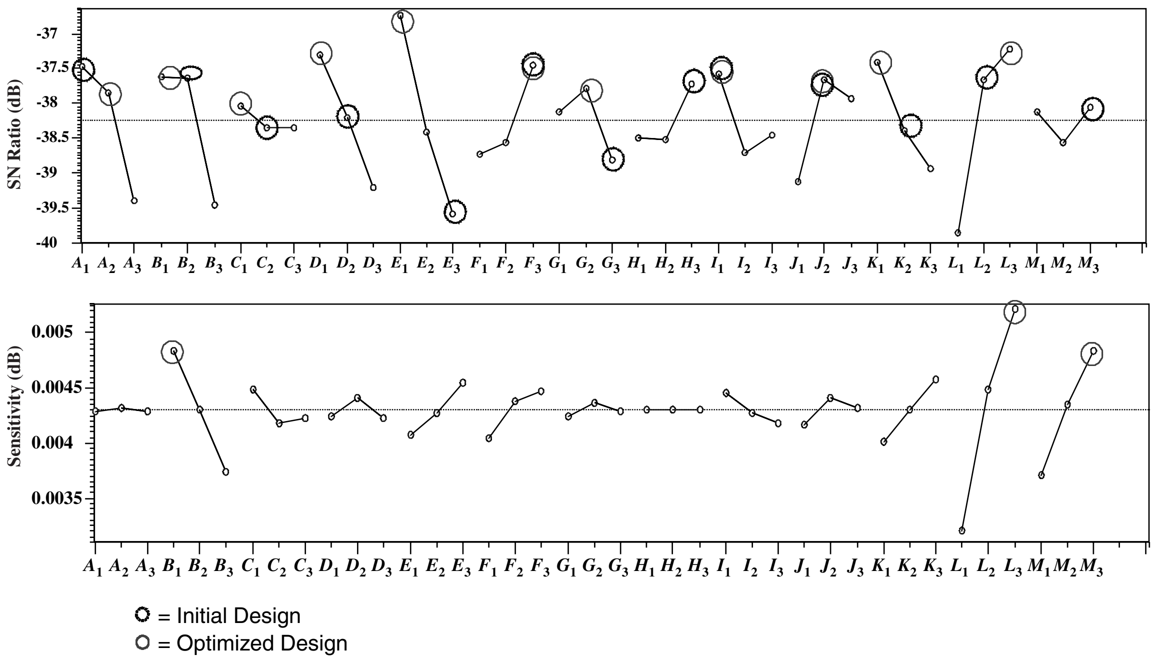


Figure 7
SN ratio and sensitivity plots

Table 3
Two-step optimization

	Control Factor												
	A	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***	***J***	***K***	***L***	***M***
Original	1	2	2	2	3	3	3	3	1	2	2	2	3
SN ratio (first step)	1	1	1	1	1	3	2	3	1	2	1	3	3
Sensitivity (second step)		1										3	3
Optimized	2	1	1	1	1	3	2	3	1	2	1	3	3

Table 4
Model confirmation

Condition	SN		Sensitivity	
	Prediction	Confirmation	Prediction	Confirmation
Optimum	−29.1	−32.2	0.0048	0.0049
Current	−35.65	−38.02	0.0041	0.0041
Improvement (dB)	6.55	5.82	0.0007	0.0008
Variation reduction (%)	53	49	17	19

magnetic package, is shown in Table 1 and Figure 6.

Experimental Layout An L_{36} orthogonal array was selected and used to perform the experiment (Table 2), so that we could study three levels of each control factor using only 13 columns.

Data Analysis and Two-Step Optimization The data were analyzed using the dynamic SN ratio:

$$\eta = 10 \log \frac{S_\beta - V_e}{rV_e} \qquad (7)$$

where S_β is the sum of the squares of distance between zero and the least squares best-fit line (forced through zero) for each data point, V_e the mean square (variance), and r the sum of squares of the signals. (*Note:* The same dynamic SN ratio cited earlier was used in each experiment.)

Figure 7 illustrates the main effects of each control factor at the three different sources. The effect of a factor level was given by the deviation of the response from the overall mean due to the factor level. The main effects plots show which factor levels are best for increasing the SN ratio. They should give the best response with the smallest effect due to noise.

Control factor settings were selected to maximize the SN ratio, minimizing the sensitivity to the noise factor (initial point) under study, providing a uniform linearity regardless of the travel position. The optimum nominal settings selected are shown in Table 3 and the model confirmation is given in Table 4.

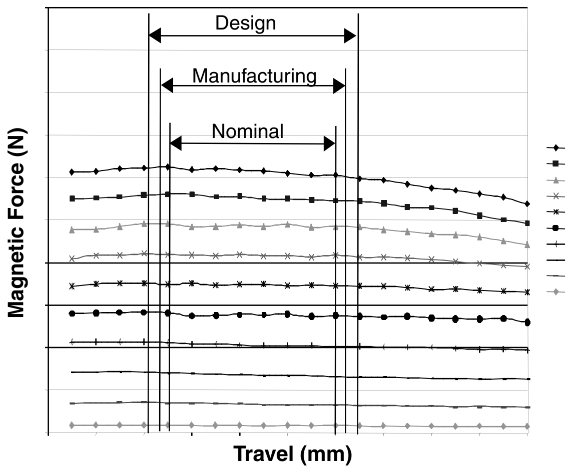
In robust design experiments, the level of improvement is determined by comparing the SN ratio of the current design to the optimized design. An improvement in SN ratio signifies a reduction in variability. In this case the gain (SN ratio in decibels) is 5.82 dB; this represents a reduction in the variation about 49% from the original design using the following formula:

$$\text{variability improvement} = \left(\tfrac{1}{2}\right)^{\text{Gain}/6} \times \text{initial variability} \qquad (8)$$

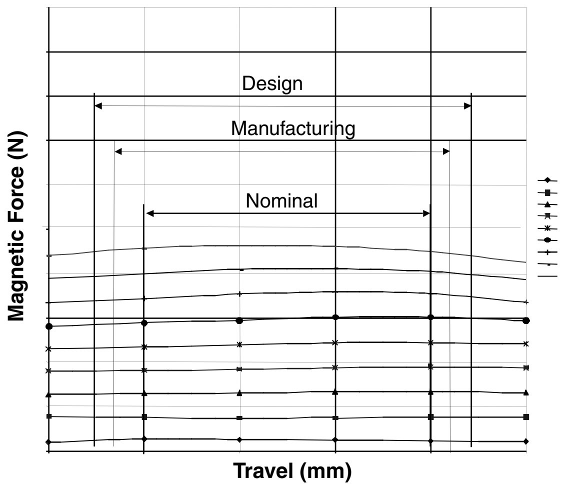
Results A significant improvement in the linearity at different initial points of the solenoid was achieved. As can be seen in Figure 8, about 50% of the linearity was gained between the original and the optimized designs. The magnetic force was increased considerably. The β value increased slightly at the beginning of the excitation of the solenoid. Therefore, we expect an earlier opening point.

Ideal Function for the Spring Package

A spring element's function is to regulate the plunger position and movement. For this package the input was the magnetic force, with results shown in Figure 9. The design of the spring element for the linear proportional solenoid is based on the fact that the travel is proportional to the magnetic force



Before Robust Engineering Optimization
(0.7 mm Linear Nominal Travel)



After Robust Engineering Optimization
(1.5 mm Linear Nominal Travel)

Figure 8
Performance of the magnetic package before and after robust engineering

(main excitation). The ideal function for this package is shown in Figure 10. The second robust design experiment we conducted was on the travel (millimeters) of the spring package.

Signal and Noise Strategies Three levels of the magnetic force (newtons) were selected: force 1, force 2, and force 3, which represent the total range of the magnetic force on operation conditions. The model (vacuum/area) was the principal source that cannot be controlled during normal operation of the solenoid and was treated as a noise factor for this experiment. This strategy reduced the mechanical response variation due to the pneumatic forces generated by the orifice diameter variation and vacuum variation.

Control Factors and Levels Table 5 gives the layout for control factors and levels. The parameter diagram, illustrating the relationship of the control factors, noise factors, signal factor, and the response to the subsystem of the spring package, is shown in Figure 11.

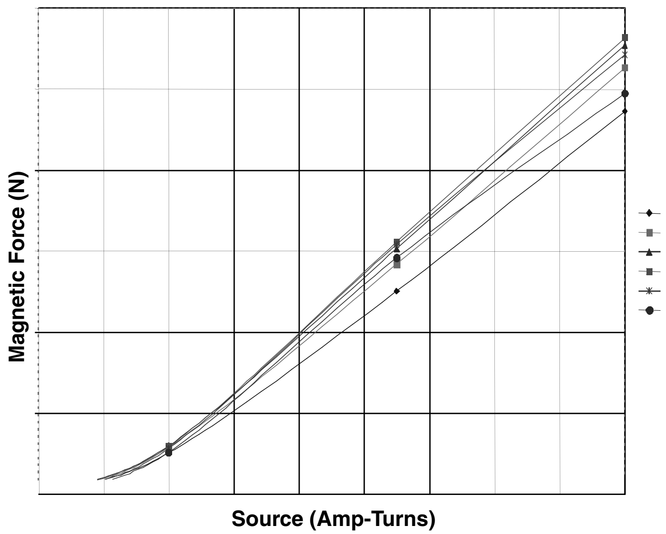
Experimental Layout An L_{18} orthogonal array was selected and used to perform the experiment (Figure 12), so that we could study two levels of one control factor and three levels of the three other control factors.

Data Analysis and Two-Step Optimization The data were analyzed using the dynamic SN ratio with equation (7).

Figure 13 illustrates the main effects of each control factor at the three sources. The effect of a factor level is given by the deviation of the response from the overall mean due to the factor level. The main effects plots show which factor levels are best for increasing the SN ratio. They should give the best response with the smallest effect due to noise.

Control factor settings were selected to maximize the SN ratio, minimizing the sensitivity to the noise factor (vacuum/area) under study, providing a uniform linearity of travel regardless of the pneumatic force. The optimum nominal settings selected are shown in Table 6.

Confirmation and Improvement in the SN Ratio Table 7 shows the predictions and confirmatory data. In robust design experiments, the level of improvement is determined by comparing the SN ratio of the current design to the optimized design.



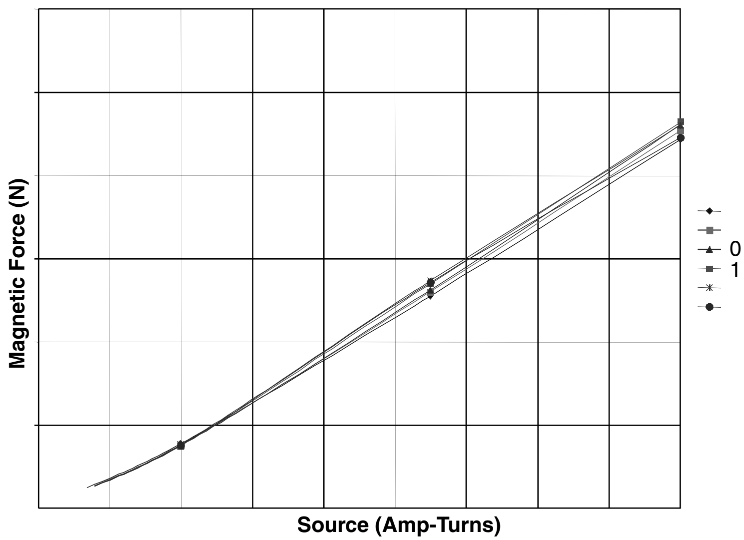


Figure 9
Ideal function

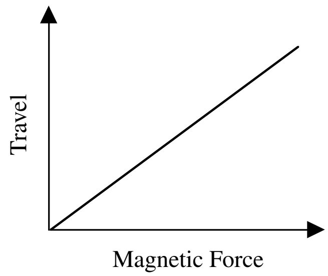


Figure 10
Ideal function

An improvement in SN ratio signifies a reduction in variability. In this case the gain (SN ratio in decibels) is 3.62 dB; this represents a reduction in the variation by about 34% from the original design using equation (8). Performance improvement results are shown in Figure 14.

A linear excitation force was obtained earlier by optimizing the magnetic package combined with the spring package. The offset between the curves in Figure 14 is a function of the effects of the vacuum force compared to the magnetic and spring forces. This offset could be reduced by making the resultant of forces less sensible to vacuum variation.

Ideal Function for the Flow Package

The purpose of the flow package is to control flow through the solenoid. For this package the input is the position of the plunger (travel). The design of the magnetic package for linear proportional solenoid is based on flow being proportional to the movement of the mobile part of the valve. The ideal function for this package is shown in Figure 15. The third robust design experiment to be studied is the flow in standard liters per minute (slpm) out of the flow package.

Table 5
Control factors levels[a]

Factor	Level 1	Level 2	Level 3
A	With[a]	Without	—
B	Low	Average	High[a]
C	Low[a]	Average	High
D	Low[a]	Average	High

[a] Current design level.

Signal and Noise Strategies Four levels of travel (millimeters) were selected. The flow of linear proportional purge solenoid should not be unstable at a low duty cycle and should have a high hysteresis, due to the effects of varying environmental factors. High and low temperature and vacuum conditions lead to poor flow performance. Therefore, the temperature and vacuum were treated as a noise factor (two levels: low and high). They are shown in Table 8. The parameter diagram, illustrating the relationship of the control factors, noise factors, signal factor, and the response to the subsystem of the flow package is shown in Figure 16.

Experimental Layout An L_{18} orthogonal array was selected and used to perform the experiment (Figure 17), so that we could study two levels of one control factor and three levels of the four other control factors.

Data Analysis and Two-Step Optimization The data were analyzed using the dynamic SN ratio with equation (7). Figure 18 illustrates the main effects of each control factor at the three different sources. The effect of a factor level is given by the deviation of the response from the overall mean due to the factor level. The main effect plots show which factor

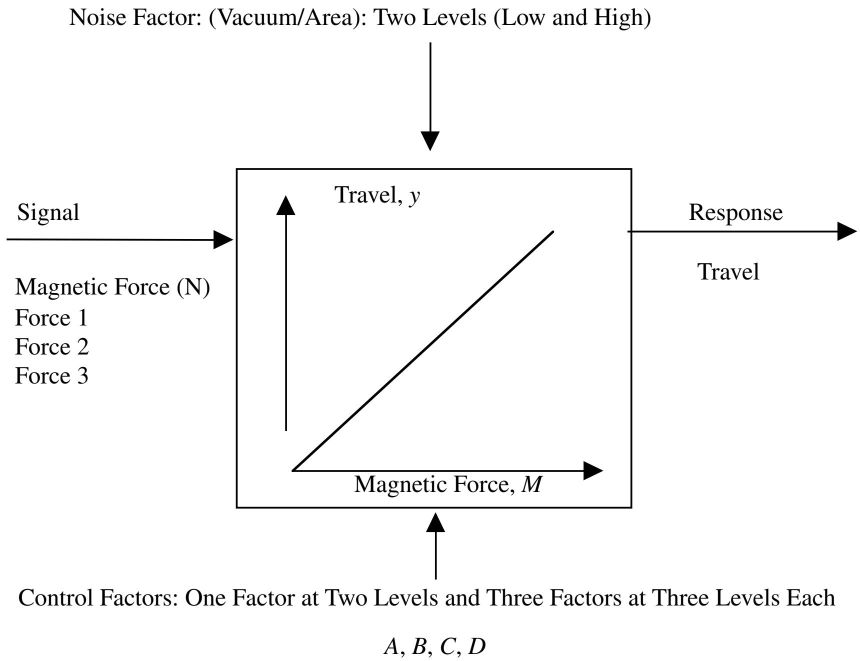


Figure 11
Parameter design

Control Factor Array

Run	A	B	C	D	Magnetic Force: 1 / Vacuum / Area: Low	1 High	2 Low	2 High	3 Low	3 High	SN	ß
1	1	1	1	1								
2	1	1	2	2								
3	1	1	3	3								
4	1	2	1	1								
5	1	2	2	2								
6	1	2	3	3								
7	1	3	1	2								
8	1	3	2	3								
9	1	3	3	1			DATA					
10	2	1	1	3								
11	2	1	2	1								
12	2	1	3	2								
13	2	2	1	2								
14	2	2	2	3								
15	2	2	3	1								
16	2	3	1	3								
17	2	3	2	1								
18	2	3	3	2								

Figure 12
Experimental layout

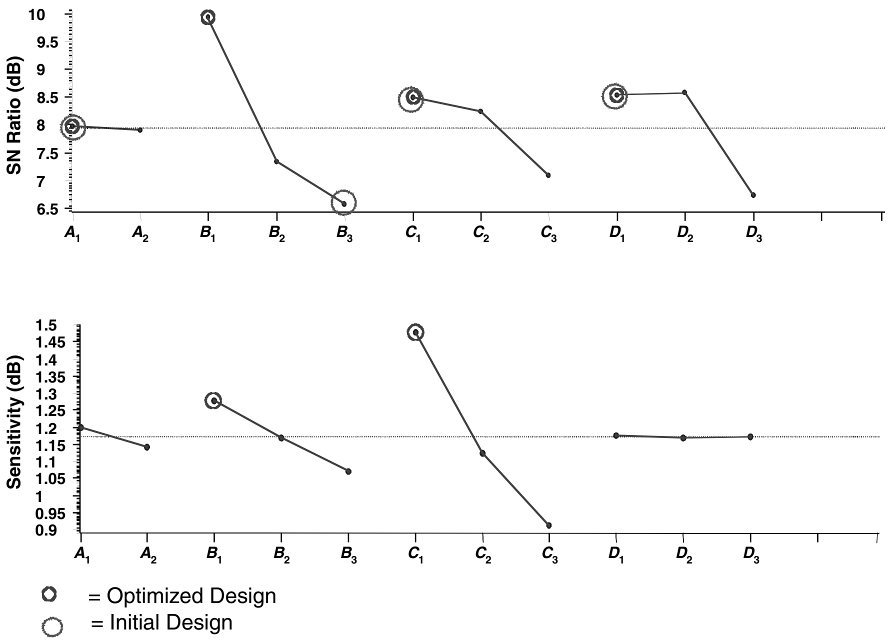


Figure 13
SN ratio and sensitivity plots

levels are best for increasing the SN ratio. They should give the best response with the smallest effect due to noise.

Control factor settings were selected to maximize the SN ratio, minimizing the sensitivity to the noise factor (vacuum/area) under study, providing a uniform linearity of travel regardless of the pneumatic force. The optimum nominal settings selected are shown in Table 9. Confirmation and improvement in the SN ratio are shown in Table 10.

Table 6
Two-step optimization

	Control Factor			
	A	*B*	*C*	*D*
Initial design	A_1	B_3	C_1	D_1
SN ratio (first step)	A_1	B_1	C_1	D_1
Sensitivity (second step)			C_1	
Optimized	A_1	B_1	C_1	D_1

In robust design experiments, the level of improvement is determined by comparing the SN ratio of the current design to the optimized design. An improvement in SN ratio signifies a reduction in variability. In this case the gain (SN ratio) is 8.13 dB; this represents a reduction in variation by about 61% from the original design using equation (8). Performance improvement results are shown in Figure 19.

The full flow or maximum flow has been improved and has become insensitive to the effect of the vacuum and temperature level, in such a manner reducing the flow variation at different vacuums that can exist in actual conditions.

7. Summary

The largest contributors to the SN ratio for the magnetic package were, in order of importance, *E, L, A,*

Table 7
Model confirmation

Condition	SN Prediction	SN Confirmation	Sensitivity Prediction	Sensitivity Confirmation
Optimum	11.11	10.66	1.62	1.63
Current	7.73	7.04	1.37	1.37
Improvement (dB)	3.38	3.62	0.21	0.26
Variation reduction (%)	32.3	34	15	19

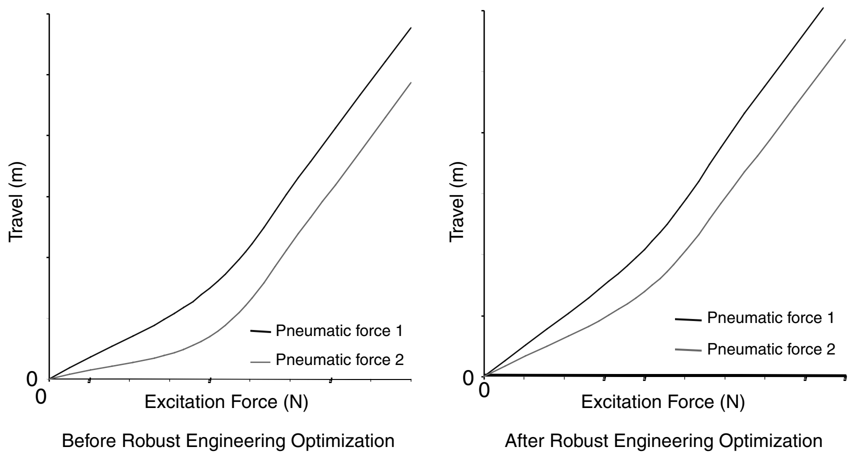


Figure 14
Improvement results

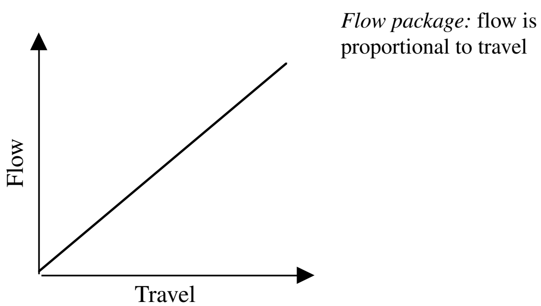


Figure 15
Ideal function

Table 8
Control factors and levels[a]

Factor	Level 1	Level 2	Level 3
A	Small[a]	Medium	Large
B	Low	Average[a]	High[a]
C	Low[a]	Average	High
D	Low	Average[a]	High
E	Small[a]	Medium	Large

[a] Current design level.

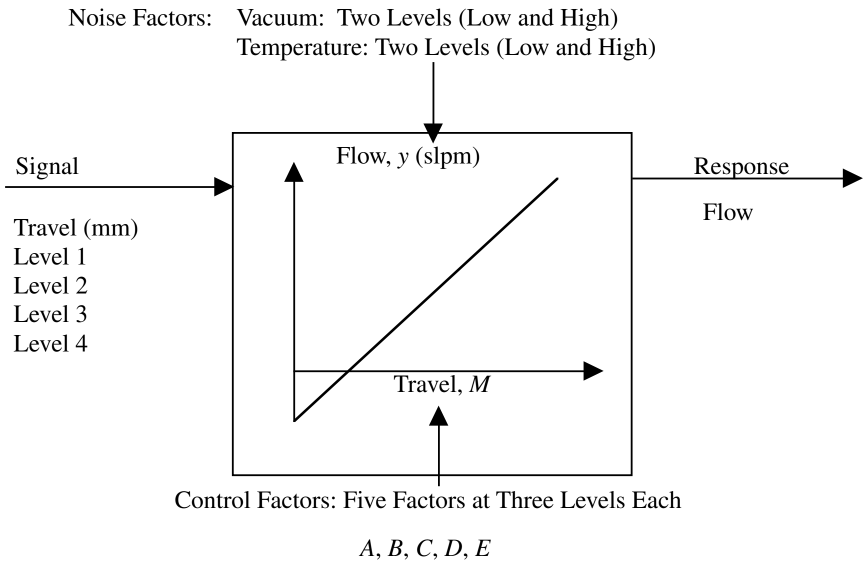


Figure 16
Parameter design

					Travel	**Level 1**				**Level 2**				**Level 3**				**Level 4**				**SN**	**β**
					Temp.	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**	**L**	**H**		
					Vacuum	**L**	**L**	**H**	**H**	**L**	**L**	**H**	**H**	**L**	**L**	**H**	**H**	**L**	**L**	**H**	**H**		
No.	***A***	***B***	***C***	***D***	***E***																		
1	1	1	1	1	1																		
2	1	2	2	2	2																		
3	1	3	3	3	3																		
4	2	1	1	2	2																		
5	2	2	2	3	3																		
6	2	3	3	1	1																		
7	3	1	2	1	3																		
8	3	2	3	2	1						**DATA**												
9	3	3	1	3	2																		
10	1	1	3	3	2																		
11	1	2	1	1	3																		
12	1	3	2	2	1																		
13	2	1	2	3	1																		
14	2	2	3	1	2																		
15	2	3	1	2	3																		
16	3	1	3	2	3																		
17	3	2	1	3	1																		
18	3	3	2	1	2																		

Figure 17
Experimental layout

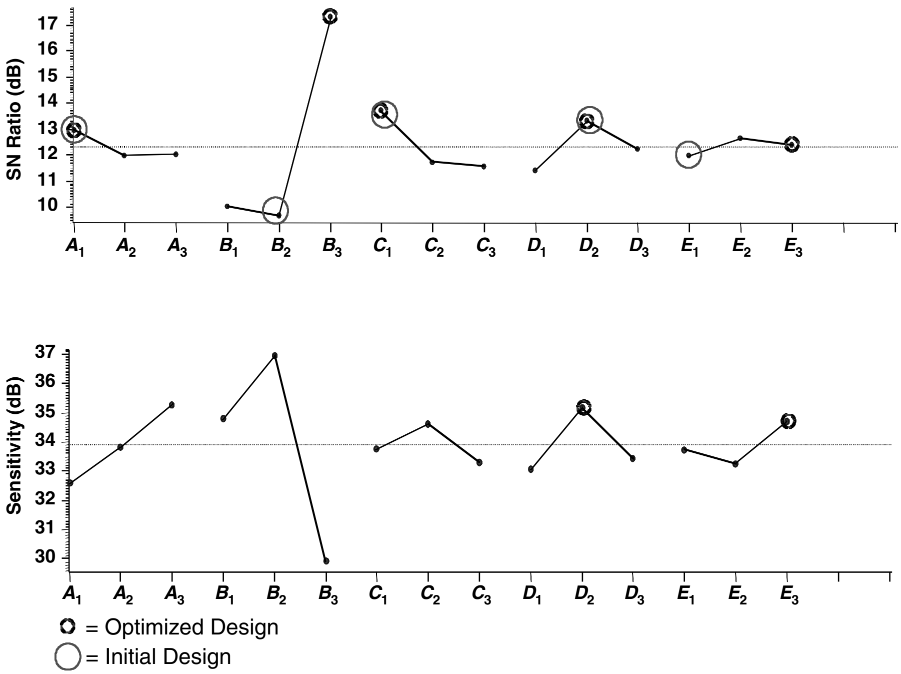


Figure 18
SN ratio and sensitivity plots

D, B, and *K*. *C* contributed little to the SN ratio. The optimized control factor settings for the magnetic package are *L, M,* and *B*. A trade-off for the control factor *A* between the levels A_1 and A_2 was made for manufacturing concerns and cost.

The largest contributors to the SN ratio for the spring package were, in order of importance, *B* and *D*. *A* contributed little to the SN ratio. The optimized control factor settings for the spring package is *C*.

The largest contributors to the SN ratio for the flow package were, in order of importance, *B, C,* and *D*. *A* contributed little to the SN ratio. The optimized control factor settings for the magnetic package is *B*.

Table 9
Two-step optimization

	Control Factor				
	A	***B***	***C***	***D***	***E***
Original	A_1	B_2	C_1	D_2	E_1
SN ratio (first step)	A_1	B_3	C_1	D_2	E_2
Sensitivity ratio (second step)				D_2	E_3
Optimized	A_1	B_3	C_1	D_2	E_3

8. Conclusions

The linear purge solenoid was broken down into subsystems. Decoupling subassemblies and components from the system allows more efficient and manageable experiments. The β values can be tuned for optimum system performance when the subassemblies and components are reassembled into the system. In this case verification and confirmation of the system level with the optimized condition of each subsystem will be pursued when the hardware becomes available.

Table 10
Model confirmation

Condition	SN Prediction	SN Confirmation	Sensitivity Prediction	Sensitivity Confirmation
Optimum	20.37	21.57	30.64	32.52
Current	12.31	13.44	29.32	29.61
Improvement (dB)	8.06	8.13	1.32	2.91
Variation reduction (%)	60.5	61	4.5	10

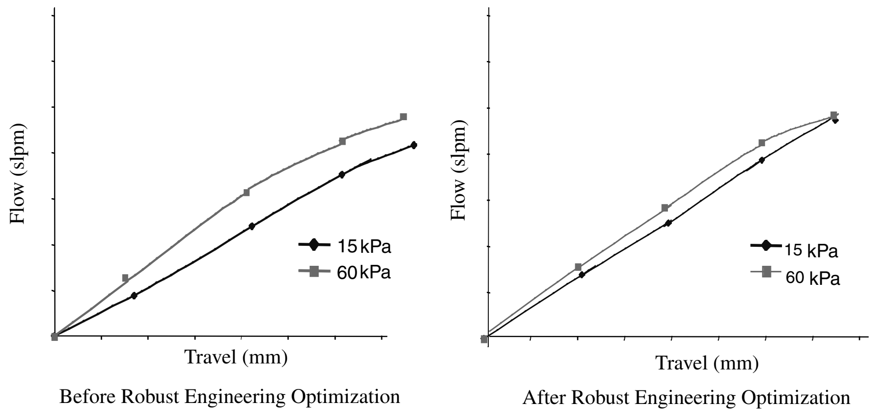


Figure 19
Performance of the flow package before and after robust engineering

The functional block diagram is a powerful tool in the design process. We should consider the confirmation run for best-case and worst-case conditions to prove the exactness of the simulation configuration and calculation. Robust engineering as part of the design concept defines the critical features on the design concepts at the early stages of development and allows for faster definition of the best concept.

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Reference

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