Part V

Software Testing and Application

Algorithms (Cases 81–82)
Computer Systems (Case 83)
Software (Cases 84–87)

CASE 81

Optimization of a Diesel Engine Software Control Strategy

Abstract: A zero-point-proportional dynamic SN ratio was used to quantify vibration and tracking accuracy under six driving conditions, which represented noise factors. An L_{18} orthogonal array explored combinations of six software strategy control factors associated with controlling fuel delivery to the engine. The result was a 4- to 10-dB improvement in vibration reduction, resulting in virtual elimination of the hitching condition. As a result of this effort, an $8 million warranty problem was eliminated. The robust design methodology developed in this application may be used for a variety of applications to optimize similar feedback control strategies.

1. Introduction

What makes a problem difficult? Suppose that you are assigned to work on a situation where (1) the phenomenon is relatively rare; (2) the phenomenon involves not only the entire drive train hardware and software of a vehicle, but specific road conditions are required to initiate the phenomenon; (3) even if all conditions are present, the phenomenon is difficult to reproduce; and (4) if a vehicle is disassembled and then reassembled with the same parts, the phenomenon may disappear completely!

For many years, various automobile manufacturers have occasionally experienced a phenomenon like this associated with slow oscillation of vehicle rpm under steady pedal position (ringing) or cruise-control conditions (hitching). Someone driving a vehicle would describe hitching as an unexpected bucking or surging of the vehicle with the cruise control engaged, especially under load (as in towing). Engineers define hitching as a vehicle in speed-control mode with engine speed variation of more than 50 rpm (peak to peak) at a frequency below 16 Hz.

A multifunction team with representatives from several areas of three different companies was brought together to address this issue. Their approaches were more numerous than the team members and included strategies ranging from studies of hardware variation to process FMEAs and dynamic system modeling. The situation was resolved using TRIZ and robust design. The fact that these methods worked effectively and efficiently in a complex and difficult situation is a testament to their power, especially when used in tandem.

TRIZ, a methodology for systemic innovation, is named for a Russian acronym meaning "theory of inventive problem solving." Anticipatory failure determination (AFD), created by Boris Zlotin and Alla Zusman of Ideation, is the use of TRIZ to anticipate failures and determine root cause. Working with Vladimir Proseanic and Svetlana Visnepolschi of Ideation, Dmitry Tananko of Ford applied TRIZ AFD to the hitching problem. Their results, published in a case study presented at the Second Annual Altshuller Institute for TRIZ Studies Conference, found that resources existed in the system to support seven possible hypotheses associated with hitching. By focusing on system conditions and circumstances associated with the phenomenon, they narrowed the possibilities to one probable hypothesis, instability in the controlling system.

By instrumenting a vehicle displaying the hitching phenomenon, Tananko was able to produce the plot shown in Figure 1. This plot of the three main signals of the control system (actual rpm, filtered rpm, and MF_DES, a command signal) verified the AFD hypothesis by showing the command signal out of phase with filtered rpm when the vehicle was kept at constant speed in cruise-control mode.

Actual rpm is out of phase with the command signal because of delays associated with mass inertia. In addition, the filtered rpm is delayed from the actual rpm because of the time it takes for the filtering calculation. The specific combination of these delays, a characteristic of the unified control system coupled with individual characteristics of the drive train hardware, produces the hitching phenomena. The solution lies in using Taguchi's techniques to make the software/hardware system robust.

2. System Description

A simple schematic of the controlling system is shown in Figure 2. The mph set point is determined by the accelerator pedal position or cruise-control setting. Depending on a number of parameters, such as vehicle load, road grade, and ambient temperature, the control system calculates the amount of fuel to be delivered for each engine cycle as well as other fuel delivery parameters. Accordingly, the engine generates a certain amount of torque, resulting in acceleration/deceleration of the vehicle. The feedback loop parameters and the speed sensor parameters must be set at appropriate values to achieve smooth vehicle behavior with no hitching/ringing.

3. P-Diagram

The parameters studied in this project are given in the P-diagram shown in Figure 3.

4. Noise Factors

Different driving profiles constitute important noise factors because they cause major changes to the load on the engine. The following six noise levels were used in this experiment:

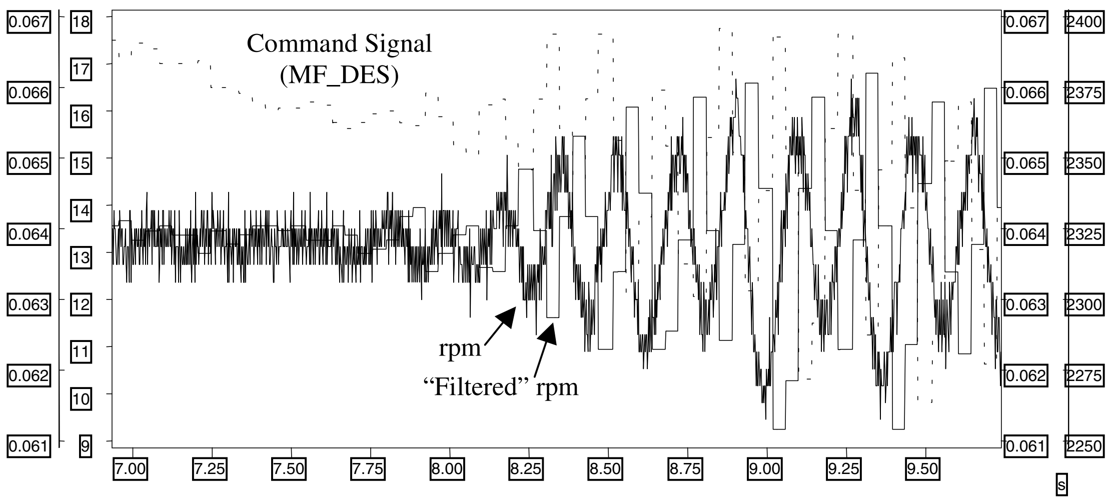


Figure 1
Hitching phenomena

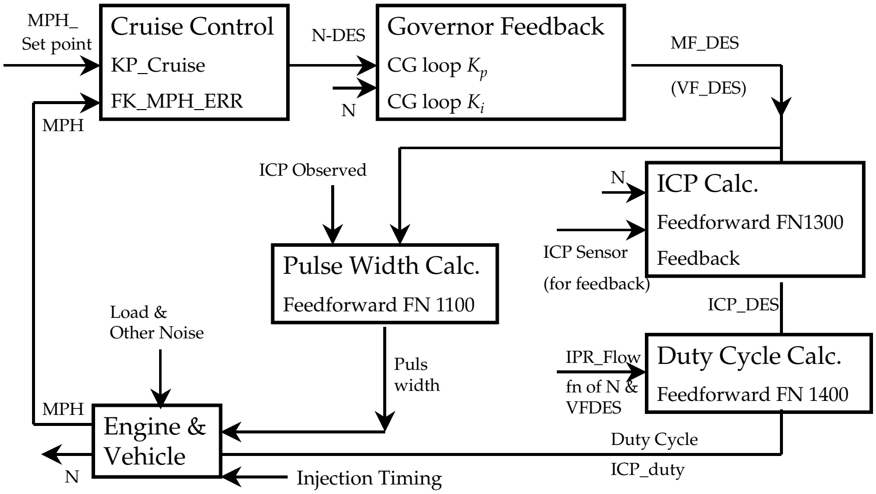


Figure 2
Simplified functional flow

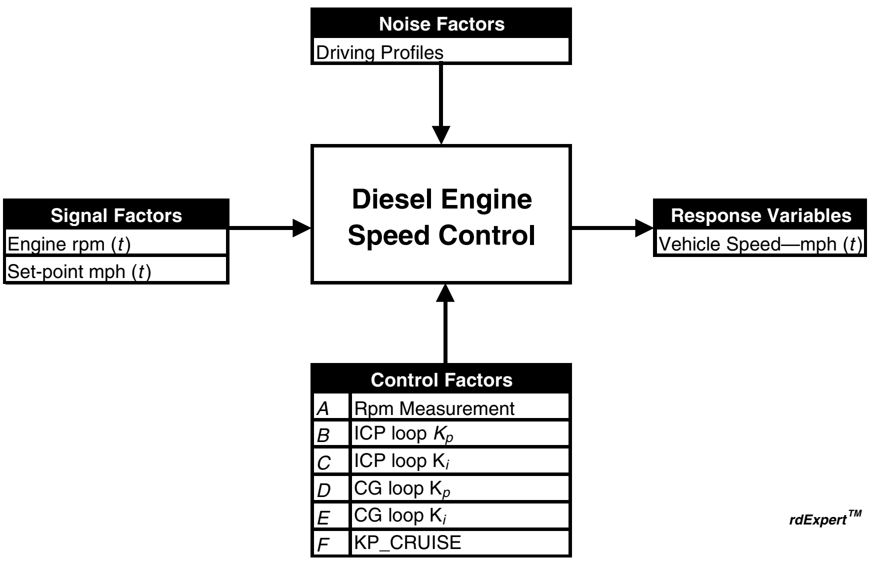


Figure 3
P-diagram

1. Accelerating in 1-mph increments from 47 to 56 mph
2. Accelerating in 1-mph increments from 57 to 65 mph
3. Decelerating in 1-mph increments from 65 to 57 mph
4. Decelerating in 1-mph increments from 56 to 47 mph
5. Rolling hill at 65 mph
6. Rolling hill 57 mph

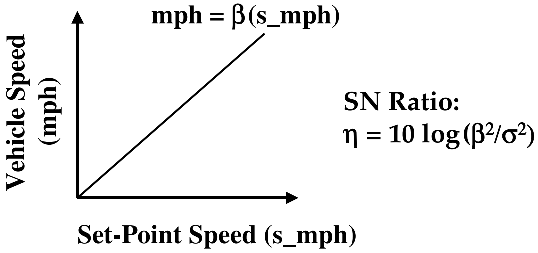


Figure 5
Ideal function 2: tracking

5. Signal Factor, Response, and Ideal Function

There would be no vibration or hitching or ringing if the vehicle speed (mph) were directly proportional to the engine speed (rpm) at every instant of time. Of course, the gear ratio was constant over the time period considered. Thus, the ideal function selected was zero-point-proportional with scaled engine rpm as the signal and vehicle speed (mph) as the response (Figure 4). The scale depends on the gear ratio and tire type.

While eliminating hitching, it is also important to have good tracking between the set-point mph and the actual mph. We need another ideal function and corresponding SN ratio, as shown in Figure 5.

6. Control Factors

The six control factors listed in Table 1 were selected for the study. These factors, various software speed control strategy parameters, are described below:

A: Rpm measurement is the number of consecutive measurements over which the rotational speed is averaged for estimating rpm.

B: ICP loop K_p is the proportional constant for the ICP loop.

C: ICP loop K_i is the integral constant for the ICP loop.

D: CG loop K_p is the proportional constant for the governor feedback.

E: CG loop K_i is the integral constant for the governor feedback.

F: KP_CRUISE is the proportional constant for the cruise-control feedback loop.

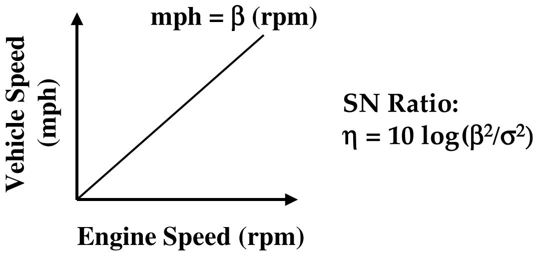


Figure 4
Ideal function 1: hitching

7. Experiment Plan and Data

An L_{18} orthogonal array was used for conducting the experiments (see Table 2). For each experiment, the vehicle was driven under the six noise conditions. Data for rpm, mph set point, and actual mph were collected using Tananko's vehicle instrumentation. About 1 minute's worth of data were collected for each noise condition. Plots of scaled rpm (signal factor) versus actual mph (response) were used for calculation of the zero-point-proportional dynamic SN ratios. Plots for two experiments, showing low and high values for the SN ratio in the L_{18} experiment [corresponding to pronounced hitching (experiment 6) and minimal hitching (experiment 5)], are shown in Figure 6*a* and *b*, respectively. The corresponding SN ratios were -1.8 and 11.8. This is an empirical validation that the SN ratio is

Table 1
Control factors and levels

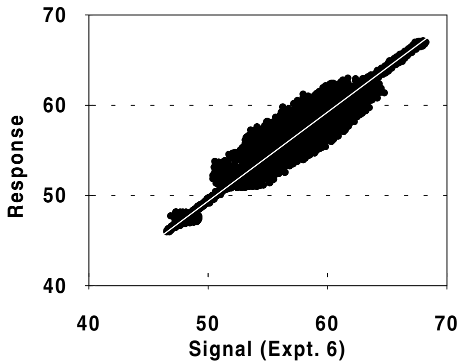
	Control Factor	No. of Levels	Level 1	Level 2	Level 3
A:	Rpm measurement	2	6 teeth	12 teeth	
B:	ICP loop K_p	3	0.0005	0.0010	0.0015
C:	ICP loop K_i	3	0.0002	0.0007	0.0012
D:	CG loop K_p	3	0.8[a]	fn[a]	1.2[a]
E:	CG loop K_i	3	0.027	0.032	0.037
F:	KP_CRUISE	3	0	0.5[a]	[a]

[a] Current level.

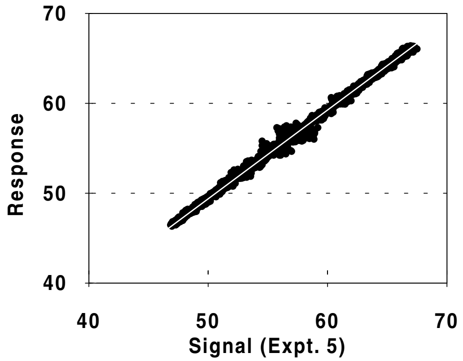
Table 2
Control factor orthogonal array[a]

No.	*A*: Col. 1 rpm Measurement	*B*: Col. 2 ICP loop K_p	*C*: Col. 3 ICP loop K_i	*D*: Col. 4 CG loop K_p	*E*: Col. 5 CG loop K_i	*F*: Col. 6 KP_CRUISE
1	(1) 6 teeth	(1) 0.0005	(1) 0.0002	(1) 0.8[b]	(1) 0.027	(1) 0
2	(1) 6 teeth	(1) 0.0005	(2) 0.0007	(2) fn[b]	(2) 0.032	(2) 0.5[b]
3	(1) 6 teeth	(1) 0.0005	(3) 00012	(3) 1.2[b]	(3) 0.037	(3) [b]
4	(1) 6 teeth	(2) 0.0010	(1) 0.0002	(1) 0.8[b]	(2) 0.032	(2) 0.5[b]
5	(1) 6 teeth	(2) 0.0010	(2) 0.0007	(2) fn[b]	(3) 0.037	(3) [b]
6	(1) 6 teeth	(2) 0.0010	(3) 0.0012	(3) 1.2[b]	(1) 0.027	(1) 0
7	(1) 6 teeth	(3) 0.0015	(1) 0.0002	(2) fn[b]	(1) 0.027	(3) [b]
8	(1) 6 teeth	(3) 0.0015	(2) 0.0007	(3) 1.2[b]	(2) 0.032	(1) 0
9	(1) 6 teeth	(3) 0.0015	(3) 00012	(1) 0.8[b]	(3) 0.037	(2) 0.5[b]
10	(2) 12 teeth	(1) 0.0005	(1) 0.0002	(3) 1.2[b]	(3) 0.037	(2) 0.5[b]
11	(2) 12 teeth	(1) 0.0005	(2) 0.0007	(1) 0.8[b]	(1) 0.027	(3) [b]
12	(2) 12 teeth	(1) 0.0005	(3) 00012	(2) fn[b]	(2) 0.032	(1) 0
13	(2) 12 teeth	(2) 0.0010	(1) 0.0002	(2) fn[b]	(3) 0.037	(1) 0
14	(2) 12 teeth	(2) 0.0010	(2) 0.0007	(3) 1.2[b]	(1) 0.027	(2) 0.5[b]
15	(2) 12 teeth	(2) 0.0010	(3) 00012	(1) 0.8[b]	(2) 0.032	(3) [b]
16	(2) 12 teeth	(3) 0.0015	(1) 0.0002	(3) 1.2[b]	(2) 0.032	(3) [b]
17	(2) 12 teeth	(3) 0.0015	(2) 0.0007	(1) 0.8[b]	(3) 0.037	(1) 0[b]
18	(2) 12 teeth	(3) 0.0015	(3) 00012	(2) fn[b]	(1) 0.027	(2) 0.5[b]

[a] Level in parentheses.
[b] Current condition.



(*a*)



(*b*)

Figure 6
Data plots for hitching ideal function

capable of quantifying hitching. See Table 3 for the SN ratio from each run of L_{18}.

8. Factor Effects

Data from the L_{18} experiment were analyzed using *rdExpert* software developed by Phadke Associates, Inc. The control factor orthogonal array is given in the appendix to the case. The signal-to-noise (SN) ratio for each factor level is shown in Figure 7. From the analysis shown in the figure, the most important factors are *A*, *D*, and *F*.

1. Factor *A* is the number of teeth in the flywheel associated with rpm calculations. The more teeth used in the calculation, the longer the time associated with an rpm measurement and the greater the smoothing of the rpm measure. Level 2, or more teeth, gives a higher SN ratio, leading to reduced hitching.
2. Factor *D* is CG loop K_p, a software constant associated with gain in the governor loop. Here level 1, representing a decrease in the current function, is better.
3. Factor *F* is KP_CRUISE, a software constant in the cruise control strategy associated with gain. Level 3, maintaining the current value for this function, is best, although level 2 would also be acceptable.

Confirmation experiments using these factors were then conducted. Predicted values and observed values were computed for the best levels of factors, the worst levels of factors, and the vehicle baseline (original) levels of factors.

Best: A_2, B_3, C_2, D_1, E_2, F_3

Worst: A_1, B_1, C_3, D_3, E_1, F_1

Baseline: A_1, B_2, C_1, D_2, E_2, F_3

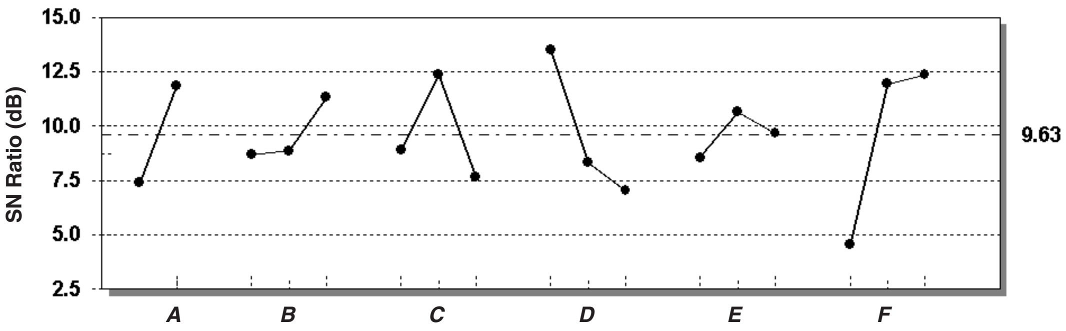
The results are shown in Table 4. We have shown the SN ratios separately for noise conditions 1–4 and 5–6 to be able to ascertain that the hitching problem is resolved under the two very different driving conditions. As can be seen in this table, there was very good agreement between the predicted and observed SN ratios under the foregoing conditions.

The confirmatory experiment plot of rpm versus mph for the best factor combination is shown in Figure 8. This plot clearly supports the conclusions reached by the SN ratio analysis.

An additional SN ratio analysis of the mph set point versus vehicle speed (mph) was done to evaluate ability of the speed control software to track the set-point speed accurately. The factor effects for the tracking ideal function are shown in Figure 9. Only factor *F*, KP_CRUISE, is important for tracking. Furthermore, the direction of improvement for the tracking ideal function is the same as that for the hitching ideal function. Thus, a compromise is not needed. The confirmation results for the tracking ideal function are also given in Table 2.

Table 3
SN ratios

	Hitching SN		Tracking SN	
No.	Noises 1–4	Noises 5–6	Noises 1–4	Noises 5–6
1	2.035	9.821	3.631	−2.996
2	11.078	4.569	11.091	7.800
3	4.188	4.126	9.332	9.701
4	15.077	7.766	11.545	8.256
5	11.799	3.908	12.429	9.233
6	−1.793	3.001	3.415	−1.390
7	9.798	4.484	11.841	9.793
8	5.309	6.212	4.392	−2.053
9	8.987	8.640	9.618	9.324
10	13.763	12.885	10.569	10.267
11	18.550	18.680	12.036	14.106
12	2.538	15.337	1.826	−3.128
13	0.929	16.065	1.492	−1.200
14	9.022	9.501	8.688	7.856
15	18.171	18.008	11.260	14.804
16	11.734	11.823	12.031	11.852
17	18.394	16.338	7.000	−1.881
18	13.774	17.485	9.943	9.142
Average	9.631	10.480	8.452	6.083



F Value	5.9	0.8	2.3	4.6	0.4	7.5
%SS	13.6	3.9	10.7	21.3	2.0	34.6

Figure 7
Factor effects for ideal function 1: hitching

Table 4
Results of confirmatory experiment

	Ideal Function 1: Hitching		Ideal Function 2: Tracking	
	Noise Conditions 1–4	Noise Conditions 5–6	Noise Conditions 1–4	Noise Conditions 5–6
Best				
Observed	18.44	19.01	11.80	15.39
Predicted	21.25	17.85	12.31	12.37
Worst				
Observed	−0.04	6.45	4.04	−1.56
Predicted	−2.26	3.28	2.74	−2.89
Baseline				
Observed	14.88	9.56	12.86	10.31
Predicted	8.08	5.66	11.55	10.8

9. Further Improvements

The factor effect plots of Figures 7 and 9 indicate that improvements beyond the confirmation experiment can be achieved by exploring beyond level A_2 for factor A, below level D_1 for factor D, and beyond level F_3 for factor F. These extrapolations were subsequently tested and validated.

10. Conclusions

The team now knew how to eliminate hitching completely. Many members of this team had been working on this problem for quite some time. They believed it to be a very difficult problem that most likely would never be solved. The results of this study surprised some team members and made them believers in the robust design approach. In the words of one of the team members, “When we ran that confirmation experiment and there was no hitching, my jaw just dropped. I couldn’t believe it. I thought for sure this would not work. But now I am telling all my friends about it and I intend to use this approach again in future situations.”

After conducting only one L_{18} experiment, the team gained tremendous insights into the hitching phenomenon and how to avoid it. They understood on a root-cause level what was happening, made adjustments, and conducted a complete prove-out program that eliminated hitching without causing other undesirable vehicle side effects. As a result of this effort, an $8 million warranty problem was eliminated.

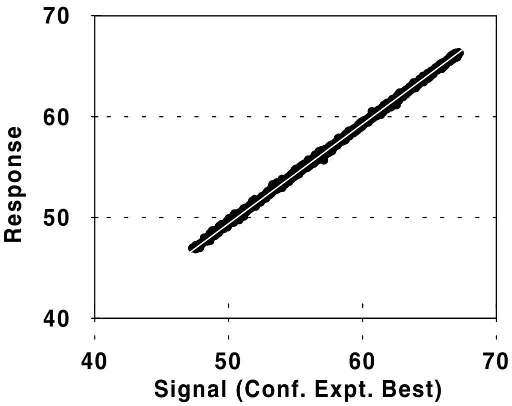


Figure 8
Plot of ideal function 1 (hitching) with best factor combination

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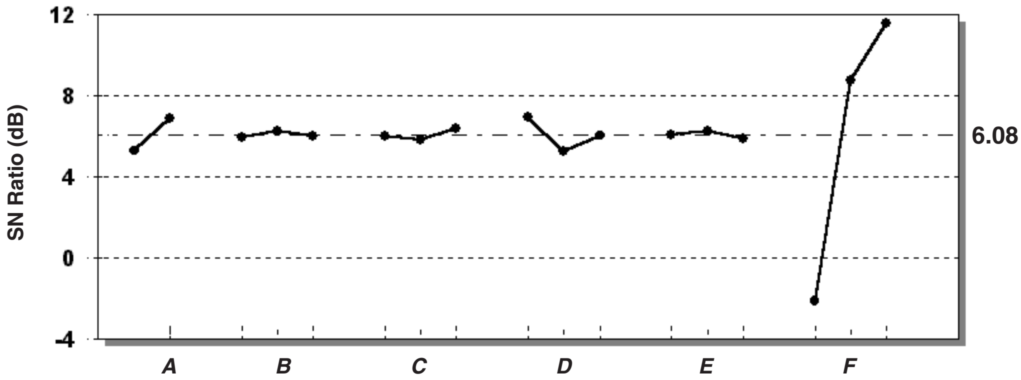

***F* Value**	4.2	0.1	0.2	1.6	0.1	118.3
% SS	1.7	0.0	0.2	1.3	0.1	94.4

Figure 9
Factor effects for the tracking ideal function

this manuscript. The data for this case were analyzed by using the *rdExpert* software developed by Phadke Associates, Inc. *rdExpert* is a trademark of Phadke Associates, Inc.

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This case study is contributed by Larry R. Smith and Madhav S. Phadke.