CASE 62

Optimal Design for a Small DC Motor

Abstract: In automobiles, dc motors are used for power windows, wipers, and other purposes. To improve quality and reduce cost, development was conducted together with the supplier of motors. In the beginning, the main objective was trying to reduce audible noise. However, the functionality, including power consumption, was evaluated through energy transformation. As a result, efficiency was improved substantially, nose level was reduced, and motor downsizing was achieved.

1. Function of a DC Motor

A dc motor has a mechanism that converts electric power (electricity, I, × voltage, V) to motive power (2 × π × no. revolutions, n, × torque, T), and their relationship is expressed as follows:

$$2\pi nT = \beta IE \qquad \text{watts} \tag{1}$$

Now β corresponds to energy conversion efficiency, and equation (1) represents a technical means per se. On the other hand, since the requirement of a motor as a product is motive power to drive a target object, if we cannot obtain the power, the motor does not work. Therefore, we regard the motive power required for a product as a signal and the required motive power with less electric power as the dc motor's function. This relationship is expressed as

$$IE = \beta \times 2\pi nT \qquad \text{watts} \tag{2}$$

Now β is considered the magnitude of electric power when a certain amount of motive power is generated, defined as *electric power consumption rate.* Thus, as shown in Figure 1, enhancing the stability for noise and reducing the electric consumption rate, β, in equation (2) are equivalent to functional improvement, and we evaluate an objective by using a means.

2. Experimental Procedure and Measurement Characteristics

In our experiment we measured the number of revolutions and internal current at intervals of 0.1 second for 180 seconds by applying a certain amount of voltage when one of three levels of torque, which simulate actual target objects, was applied to the motor. Therefore, 1800 data were recorded for each load condition by a measurement machine. However, since, judging from the total lapse of time, we concluded that we could elucidate the overall trend by using only three points of time: the initial point, the point at 90 seconds, and the point at 180 seconds. We selected only 10 data at the time interval of 1 second from the 10-second-lapsed point in each time frame, thereby obtaining a total of 30 data for each load condition. For experiment 1, Figure 2 shows the transition of electric consumption and subsequent relationship of input and output. The deviation from linearity in this input/output relationship represents nonlinear elements in the change of current for a change in electric power consumption and load torque as well as error elements when the function is evaluated. By using a motor's heat as the noise effect in a functionality evaluation, we reduced our analysis period by 50% from that under conventional conditions, by assigning temperature or deterioration to an outer array in an orthogonal array.

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

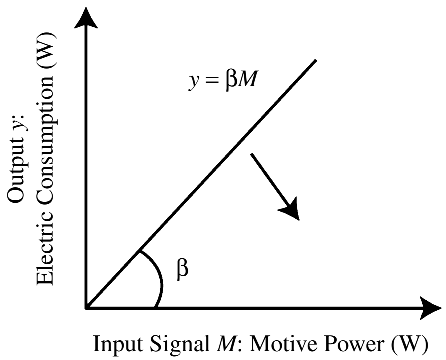

Figure 1
DC motor's function

3. SN Ratio and Sensitivity

Table 1 shows the data for experiment 1. We computed the motive power as a signal factor by multiplying by 2π the product of the measured number of revolutions, n, and the load torque, T. In addition, the power consumption as an output was equivalent to the product of the measured internal current of the motor, I, and the applied voltage, E. Since both the signal and output measured in the unit of power (watts) are characteristics related to energy, we analyzed their square roots by considering the additivity of factor effects obtained through decomposition of their variations.

Using the data of experiment 1 shown in Table 1, we detailed the calculation procedure of SN ratio and sensitivity as shown below.

Total variation:

$$S_T = 8.56^2 + 8.50^2 + \cdots + 10.14^2 + 10.06^2 = 7413.58 \qquad (f = 90) \qquad (3)$$

Effective divider:

$$r = 3.95^2 + 3.98^2 + \cdots + 4.70^2 + 4.73^2 = 1854.37 \qquad (4)$$

Linear equation:

$$L = (3.95)(8.56) + (3.98)(8.50) + \cdots + (4.70)(10.14) + (4.73)(10.06) = 3701.03 \qquad (5)$$

Variation of proportional term:

$$S_\beta = \frac{L^2}{r} = \frac{3701.03^2}{1854.37} = 7386.65 \qquad (f = 1) \qquad (6)$$

Error variation:

$$S_e = S_T - S_\beta = 7413.58 - 7386.65 = 26.93 \qquad (f = 89) \qquad (7)$$

Error variance:

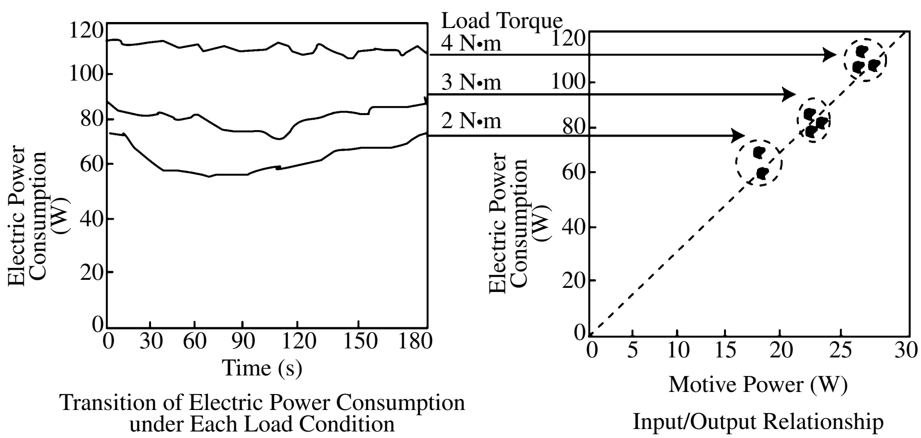

Figure 2
Input/output relationship

Table 1
Results of experiment 1

Load (Nm)	Data Type[a]	Measurement Point of Time	Fluctuation at Each Measurement Point of Time									
2	Signal *M*	Initial	3.95	3.98	3.98	3.97	3.98	3.97	4.01	4.00	3.99	4.01
	Output *y*		8.56	8.50	8.42	8.35	8.32	8.43	8.38	8.31	8.26	8.23
	Signal *M*	90-s-lapsed	4.10	4.10	4.09	4.10	4.11	4.09	4.11	4.10	4.11	4.09
	Output *y*		7.68	7.61	7.80	7.72	7.66	7.70	7.75	7.69	7.56	7.76
	Signal *M*	180-s-lapsed	4.09	4.13	4.11	4.11	4.13	4.12	4.12	4.11	4.13	4.13
	Output *y*		7.64	7.61	7.61	7.59	7.68	7.58	7.51	7.69	7.55	7.56
3	Signal *M*	Initial	4.61	4.62	4.63	4.67	4.65	4.65	4.66	4.64	4.64	4.65
	Output *y*		9.28	9.31	9.28	9.25	9.15	9.15	9.16	9.17	9.18	9.12
	Signal *M*	90-s-lapsed	4.75	4.73	4.73	4.73	4.76	4.78	4.76	4.76	4.74	4.75
	Output *y*		8.70	8.76	8.76	8.67	8.72	8.73	8.70	8.74	8.74	8.73
	Signal *M*	180-s-lapsed	4.64	4.65	4.66	4.64	4.64	4.67	4.65	4.63	4.66	4.69
	Output *y*		8.98	9.01	8.90	8.93	8.96	8.80	8.80	8.91	8.92	8.88
4	Signal *M*	Initial	4.90	4.91	4.93	4.95	4.95	4.96	4.97	4.96	4.94	4.96
	Output *y*		10.57	10.50	10.43	10.38	10.36	10.37	10.40	10.39	10.37	10.37
	Signal *M*	90-s-lapsed	4.81	4.76	4.76	4.82	4.88	4.85	4.82	4.83	4.84	4.90
	Output *y*		10.28	10.33	10.28	10.11	10.05	10.19	10.16	10.19	10.04	10.00
	Signal *M*	180-s-lapsed	4.73	4.73	4.80	4.72	4.64	4.68	4.77	4.70	4.70	4.73
	Output *y*		10.09	10.00	10.01	10.19	10.29	10.11	10.01	10.20	10.14	10.06

[a] Signal M is $\sqrt{2\pi nT}$ and output y is $\sqrt{IV}$.

$$V_e = \frac{S_e}{89} = \frac{26.93}{89} = 0.3026 \quad (8)$$

SN ratio:

$$\eta = 10 \log \frac{(1/r)(S_\beta - V_e)}{V_e}$$

$$= 10 \log \frac{(1/1854.37)(7386.65 - 0.3026)}{0.3026}$$

$$= 11.19 \text{ dB} \quad (9)$$

Sensitivity:

$$S = 10 \log \frac{1}{r} (S_\beta - V_e)$$

$$= 10 \log \frac{1}{1854.37} (7386.65 - 0.3026)$$

$$= 6.00 \text{ dB} \quad (10)$$

4. Optimal Condition and Confirmatory Experiment

As control factors we selected eight factors (Table 2) and assigned them to an L_{18} orthogonal array. For each experiment in the L_{18} orthogonal array, we calculated the SN ratio and sensitivity using the calculation method discussed in the preceding section. Based on the result, we computed the level-by-level average SN ratio and sensitivity and plotted the factor effects (Figure 3).

The optimal condition determined by the response graph of the SN ratio is shown together with the current condition as follows:

Optimal condition: $A_1B_2C_3D_1E_2F_1G_3H_3$

Current condition: $A_1B_2C_1D_3E_2F_1G_1H_1$

In Table 3 we show an estimate of the process averages of the SN ratio and sensitivity under both optimal and current conditions, together with the result of the confirmatory experiment. As a result, we confirmed good reproducibility for both the SN ratio and sensitivity. Additionally, by assessing a benchmarked product regarded as comparable to our target, we confirmed that the optimal condition is equivalent to its level.

Next, we illustrated the plot of the input/output relationship under each condition in Figure 4. Looking at the figure we can see that we can minimize the fluctuation in power consumption and reduce the power consumption rate β by 17% under current conditions and by 11% for the benchmarked product. The reduction in power

Table 2
Factors and levels

Factor	Level 1	Level 2	Level 3
Control factors			
A: fixing method for part A	Current	Rigid	—
B: thickness of part B	Small	Mid	Large
C: shape of part B	1	2	3
D: width of part D	Small	Mid	Large
E: shape of part E	1	2	3
F: inner radius of part F	Small	Mid	Large
G: shape of part G	1	2	3
H: thickness of part G	Small	Mid	Large
Signal factor			
M: motive power ($2\pi nT$)	Product of load torque and number of revolutions		
Noise factor			
I: time	Initial	90-s-lapsed	180-s-lapsed

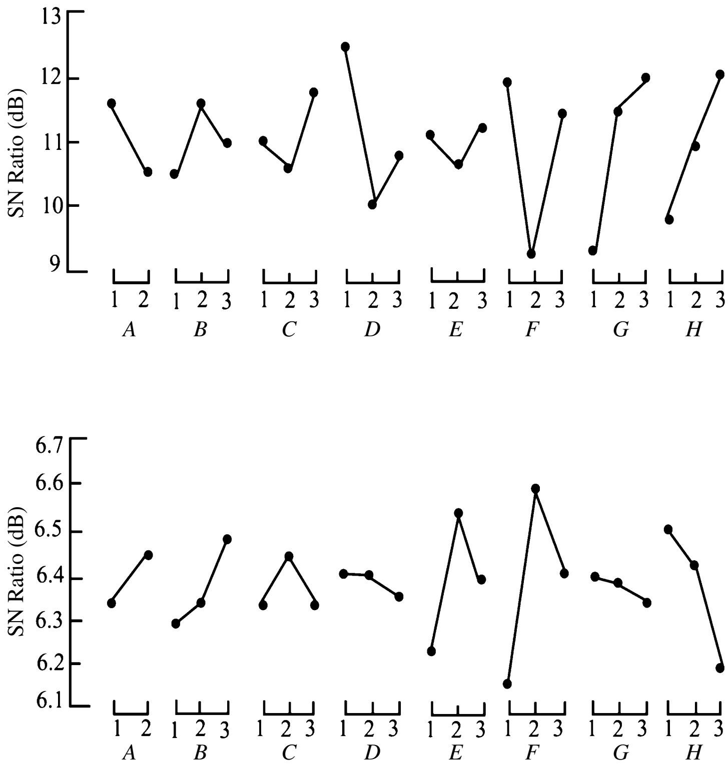

Figure 3
Response graphs

consumption enhances the motive power gained from the same power and increases the efficiency, β, by 4.3% for those under the current condition and by 2.7% for those of the benchmarked product. Owing to this achievement, we improved the motive power obtained from a car battery by 20% compared with that under current conditions. In addition, we can downsize components such a magnet or yoke without losing the current level of the motive power and, moreover, can slash material and other costs by several dozen million yen on a yearly basis.

Table 3
SN ratio and sensitivity in confirmatory experiment (dB)

	SN Ratio		Sensitivity	
Condition	**Estimation**	**Confirmation**	**Estimation**	**Confirmation**
Optimal	16.88	16.43	5.99	6.11
Current	10.06	11.73	6.31	6.93
Gain	6.82	4.70	−0.32	−0.82
Benchmark	—	16.77	—	6.62

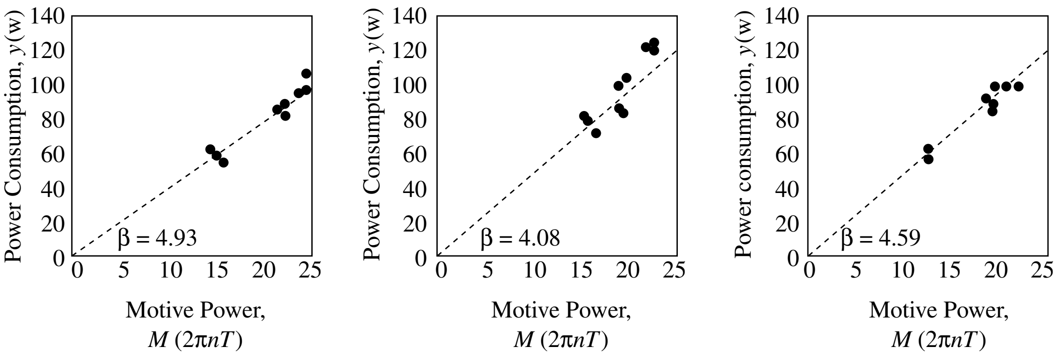

Figure 4
Results of confirmatory experiment

Reference

Kanya Nara, Kenji Ishitsubo, Mitsushiro Shimura, Akira Harigaya, Naoto Harada, and Hideki Rikanji, 2000. Parameter design for a small dc motor. *Proceedings of the 8th Quality Engineering Symposium,* pp. 194–197.

This case study is contributed by Kanya Nara.