CASE 17

Evaluation of the Generic Function of Film Capacitors

Abstract: This research focuses on parameter design to clarify (1) a generic function to express a capacitor's functionality systematically, and (2) a practical measurement process to evaluate the generic function of a film capacitor.

1. Introduction

In applying quality engineering techniques to the functional evaluation of a capacitor, we used the following characteristics: (1) the charging characteristic by direct current (dc), (2) discharging characteristic by dc, (3) voltage and current characteristics by alternating current (ac), and (4) charging and discharging characteristics by a combination of dc and ac. Additionally, to apply it only to the technological development process to meet the following conditions was desirable: (a) that a large variation in SN ratios be obtained; (b) that a voltage similar to the one in practical use be set; (c) that a test sample not come up easily with missing data, even if the sample was defective; (d) that a time constant be easy to measure.

In applying quality engineering techniques to a film capacitor, we concluded that item 4 above was appropriate because we wished to evaluate energy loss of charge and discharge at a given dc stress.

On the other hand, since a capacitor stores and discharges energy proportional to charged voltage in the form of an electric charge, if we define capacitance as C (farads) and charged voltage as V, the electrical charge accumulated, Q (coulombs), is expressed as

$$Q = CV \tag{1}$$

In our study we considered this relationship to be a basic function. We regard this as

$$y = \beta M \tag{2}$$

2. Study of Measurement

Figure 1 illustrates a measurement circuit, and Figure 2 depicts the waveforms measured. Figure 2*a* indicates the waveform of a terminal voltage given to a capacitor, and 2*b* shows the waveform of a corresponding charging or discharging current. We divided a voltage waveform of one charge-to-discharge cycle (Figure 2*a*) by 10 equal time frames and set each of 10 voltage values (V_1 to V_{10}) at each point of time (T_1 to T_{10}) to 10 different levels. However, when we analyzed them, to assess the linearity of a waveform, we combined voltage values V_1 to V_5 at charging points of time T_1 to T_5 with signal factors M_6 to M_{10}. On the other hand, by subtracting V_5 from V_6 to V_{10} at discharging points of time T_6 to T_{10}, we created V_6^* to V_{10}^* and then related each of V_{10}^* to V_6^* with M_1 to M_5 in a reverse manner.

Since we established a relationship between terminal voltage and electric charge as the generic function, we needed to integrate the current over the time. Dividing the current waveform shown in Figure 2*b* at the same 10 points of time as those used for (1), we calculated an integral of current from zero (T_0) to each point of time (the accumulated area between a current waveform and the time axis) and set each integral to each of the electrical charges Q_1 to Q_{10}. In actuality, we measured Q_1 to Q_{10} in Figure 2*b* by reading a waveform from a digital oscilloscope, computing the area at each time frame divided into 10 equal lengths, and summing up all areas. When analyzed, for the same reason as in the case of signal factors, accumulated electrical

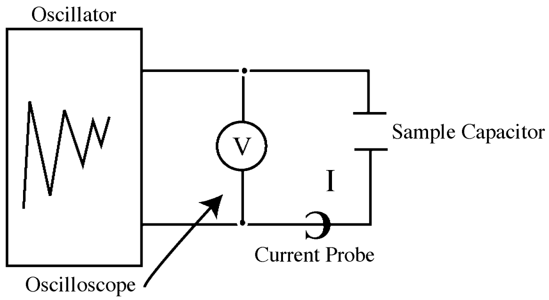


Figure 1
Measurement circuit

charges Q_{10} to Q_6 were combined with measured output values y_1 to y_5, and Q_1 to Q_5 correspond to y_6 to y_{10}.

We set a maximum voltage value to a three-level indicative factor and excluded their effects from errors. This is done because if a commercial capacitor has variations in the voltage designed, we often adjust them:

P_1: 1 kV

P_2: 2 kV

P_3: 3 kV

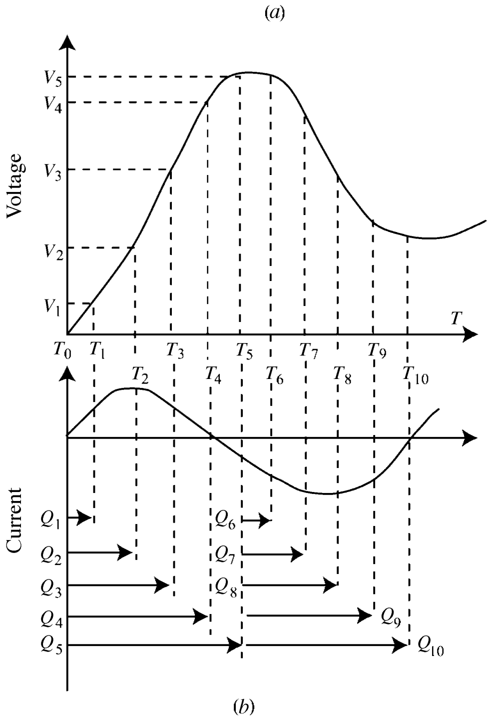


Figure 2
Waveform measured

For a noise factor, we chose two levels:

N_1: predegradation state

N_2: postdegradation state

Our experiments are conducted based on an L_{18} orthogonal array with eight factors assigned to it (Table 1).

3. SN Ratio

Table 2 shows the data for experiment 1. We computed the SN ratios and sensitivities of experiment 1, as follows.

Total variation:

$$S_T = (-11.67)^2 + (-11.05)^2 + \cdots + 127.44^2 = 169{,}473.52 \qquad (f = 60) \tag{3}$$

Six effective dividers:

$$r_1 = (-3.01)^2 + (-2.70)^2 + \cdots + 7.11^2 = 149.30$$

$$r_2 = 283.36 \qquad r_3 = 569.16 \qquad r_4 = 869.50$$

$$r_5 = 1097.47 \qquad r_6 = 1697.48 \tag{4}$$

Six linear equations:

$$L_1 = (-3.01)(-11.67) + \cdots + (7.11)(50.98) = 991.05$$

$$L_2 = 1264.93 \qquad L_3 = 3945.39 \qquad L_4 = 4558.54$$

$$L_5 = 7542.77 \qquad L_6 = 8726.45 \tag{5}$$

Variation of proportional term:

$$S_\beta = \frac{(L_1 + L_2 + L_3 + L_4 + L_5 + L_6)^2}{r_1 + r_2 + r_3 + r_4 + r_5 + r_6} = 160{,}059.15 \qquad (f = 1) \tag{6}$$

Variation of proportional term to indicative factor:

Table 1
Control factors

	Control Factor	Levels
A:	conducting film material	2
B:	pre-treatment condition	3
C:	forming temperature	3
D:	forming pressure	3
E:	forming time	3
F:	posttreatment *A*	3
G:	posttreatment B	3
H:	impregnation condition	3

$$S_{P\beta} = \frac{(L_1 + L_2)^2}{r_1 + r_2} + \frac{(L_3 + L_4)^2}{r_3 + r_4} + \frac{(L_5 + L_6)^2}{r_5 + r_6} - S_\beta$$

$$= 197.16 \qquad (f = 2) \tag{7}$$

Variation of proportional term to variability of sensitivity:

$$S_{P(N)\beta} = \frac{L_1^2}{r_1} + \frac{L_2^2}{r_2} + \frac{L_3^2}{r_3} + \frac{L_4^2}{r_4} + \frac{L_5^2}{r_5} + \frac{L_6^2}{r_6} - S_\beta - S_{P\beta}$$

$$= 4124.22 \qquad (f = 3) \tag{8}$$

Error variation:

$$S_e = S_T - S_\beta - S_{P(N)\beta} = 5092.99 \tag{9}$$

Error variance:

$$V_e = \frac{S_e}{54} = 94.31 \tag{10}$$

Combined error variance:

$$V_N = \frac{S_{P(N)\beta} + S_e}{57} = 161.71 \tag{11}$$

SN ratio:

$$\eta = 10 \log \frac{(1/r)(S_\beta - V_e)}{V_N} = -6.74 \text{ dB} \tag{12}$$

Sensitivity:

$$S = 10 \log \frac{1}{r}(S_\beta - V_e) = 15.35 \text{ dB} \tag{13}$$

4. Response Graph and Confirmatory Experiment

The SN ratios and sensitivities of experiments 1 to 18 were calculated similarly. Figure 3 illustrates the corresponding response graph. Because the coefficient of proportionality, β, in the generic function is tantamount to the capacitor's capacitance, we selected the largest-value level as the optimal config-

Table 2
Results of experiment 1

			M_1	M_2	⋯	M_{10}	r/L
P_1	N_1	M	−3.01	−2.70	⋯	7.11	r_1
		Y	−11.67	−11.05	⋯	50.98	L_1
	N_2	M	−4.26	−3.63	⋯	8.36	r_2
		Y	−25.45	−28.03	⋯	39.38	L_2
P_2	N_1	M	−7.17	−6.86	⋯	13.74	r_3
		Y	−30.25	−28.03	⋯	105.81	L_3
	N_2	M	−7.48	6.55	⋯	15.30	r_4
		Y	−48.59	−42.38	⋯	81.84	L_4
P_3	N_1	M	−8.98	−8.04	⋯	21.99	r_6
		Y	−38.81	−36.13	⋯	147.50	L_5
	N_2	M	−8.98	−8.04	⋯	21.99	r_6
		Y	−38.31	−34.69	⋯	127.44	L_6

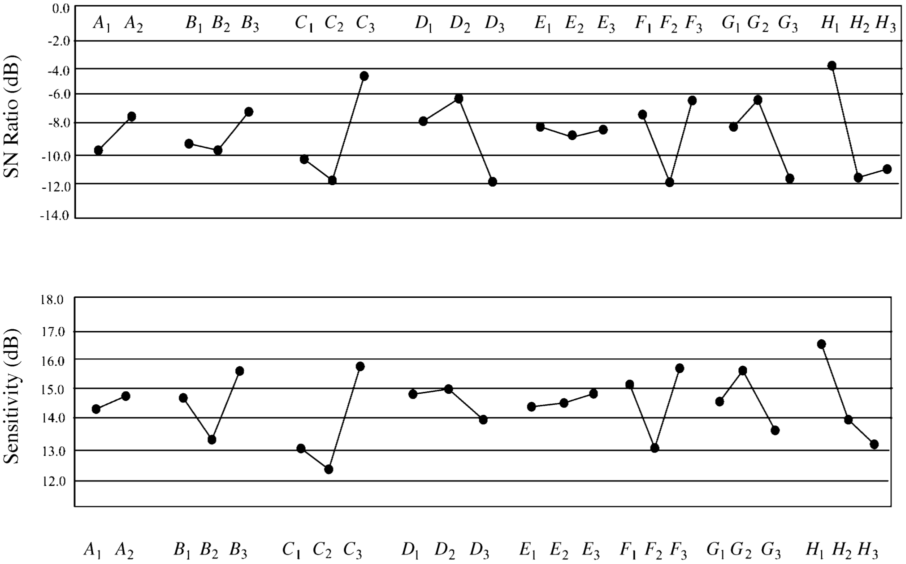


Figure 3
Response graphs

uration not only for the SN ratio but also for sensitivity. Consequently, the following configurations were chosen:

Optimal configuration: $A_2B_3C_3D_2E_1F_3G_2H_1$

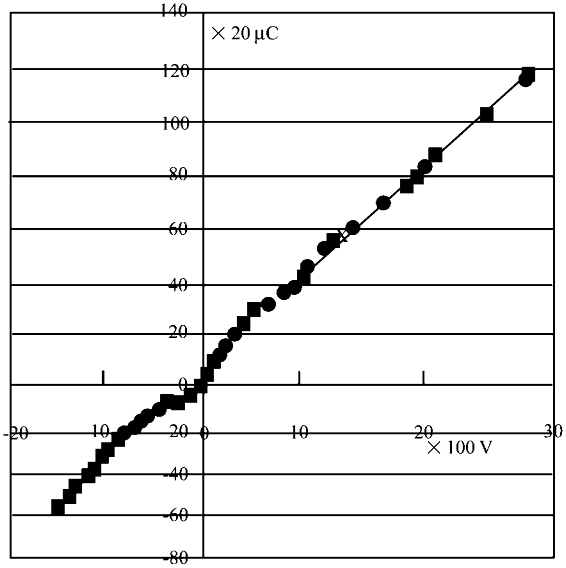
Current configuration: $A_1B_1C_2D_2E_1F_1G_1H_1$

Based on the optimal and current configurations discussed above, we prepared prototypes and implemented the same measurement and analysis. Table 3 shows the results of the confirmatory experiment. As for the SN ratio, since the difference between estimation and confirmation at the optimal configuration is small, the reproducibility can be regarded as sufficient. This was validated by the difference in the gains. However, the reproducibility of sensitivity was poor. Although we gathered that this might be due to different manufacturing conditions for prototypes that we used in the confirmatory experiment, we have not verified that assumption. Therefore, we continue to investigate this issue. Nevertheless, we do not consider it vital because there are some factors that easily control sensitivity.

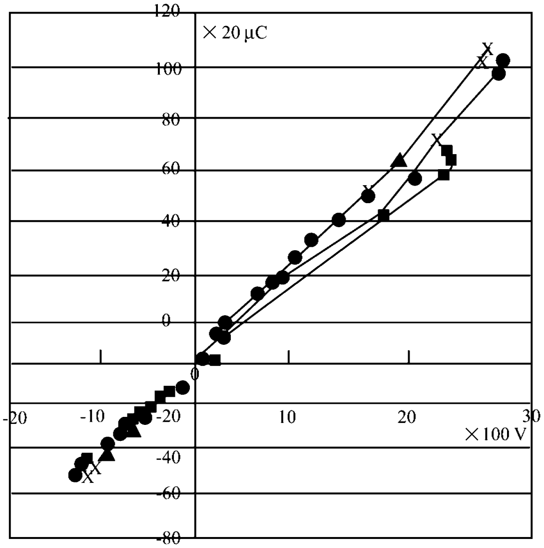
Figure 4 compares the characteristics of the optimal and current configurations. Considering the gains in SN ratio and sensitivity, we can conclude a 12.5% improvement in capacitance at the optimal configuration, and a 75% reduction in variability at

Table 3
Results of confirmatory experiment (dB)

	SN Ratio		Sensitivity	
Configuration	**Estimation**	**Confirmation**	**Estimation**	**Confirmation**
Optimal	9.81	10.69	21.43	12.69
Current	−3.63	−2.41	15.83	11.66
Gain	13.44	13.10	5.60	1.03



(*a*) Optimal Configuration



(*b*) Current Configuration

Figure 4
Characteristic of film capacitor

the optimal configuration. On the other hand, we noticed that it was unnecessary to study the indicative factor. We could conduct an equivalent experiment with only a noise factor by fixing the indicative factor at a maximum voltage (3 kV). By doing so, we could have scaled down the experiment by one-third.

Owing to the improved linearity of the generic function by parameter design, tolerable voltage, one of the important quality characteristics, was also ameliorated as follows:

Optimal configuration:	no failures with all samples up to 5.00 kV
Current configuration:	smoke-and-fire breakdowns with all samples at 4.25 kV

Reference

Yoichi Shirai, Tatsuru Okusada, and Hiroshi Yano, 1999. Evaluation of the Function for Film Capacitors. *Quality Engineering*, Vol. 7, No. 6, pp. 45–50.

This case study is contributed by Yoichi Shirai, Tatsuru Okusada, and Hiroshi Yano.