Decision Aid for Preliminary Layout Using Evaluating Function Adopting a Distance Concept* (Application to Forced-Convection Cooling Design of Electronic Systems)

Hideki KOBAYASHI**, Yukimaro MURATA***
and Naomasa NAKAJIMA****

In this paper we propose a quantitative evaluation method for the preliminary layout of electronic systems. The preliminary layout is conventionally determined by trial and error based on rough sketches by a skilled engineer. This study is based on the assumption that the skilled engineer adopts distance as the main criterion for comparison between design cases. First, a method of describing past design cases is demonstrated using similarity on the basis of a pattern attribute vector. The mahalanobis distance between design cases is formulated using this similarity, and a statistical calculation method for the evaluated function, which consists of the mahalanobis distance, is shown. A prototype of a layout design support tool was constructed to demonstrate the advantages of this evaluation method. This method is useful because of its short calculation time and the generality of its methodology.

Key Words: Design Engineering, Computer Aided Design (CAD), Pattern Recognition, Layout Design, Electronic Systems

1. Introduction

The cooling of electronic systems to increase heat dissipation density has become an important research area. The main cooling methods are natural-convection cooling, forced-convection cooling and liquid cooling. The second is the most popular method because of its excellent cost-performance. When designing a convection cooling system, the design engineer has to evaluate the temperature rise characteristics in detail under the flow pattern present in the system, because the system's flow pattern affects the

temperature of each electronic device. The engineer estimates the temperature rise using thermo-fluid dynamics simulation after deciding the preliminary layout during the initial design phase.

Generally, it is difficult for an engineer to decide the preliminary layout for the simulation model using only the constraint conditions given at the beginning. He draws a rough sketch (Fig. 1) and decides on the preliminary layout by repeatedly redrawing and evaluating it. In numerical simulation, there are quantitative evaluating functions, including those for the temperature of the devices and the atmosphere

Fig. 1 Example of rough sketch

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** Research into Artifacts, Center for Engineering (RACE), The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-0041, Japan

*** Total Energy Systems Department, Tokyo Gas Corporation, Ltd., 27 F Shinjuku Park Tower, 3-7-1 Nishi shinjuku, Shinjuku-ku, Tokyo 163-1027, Japan

**** Division of Engineering Synthesis, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

around the devices. However, in preliminary layout design, the evaluation of the preliminary layout depends on the skill of the engineer, because the criteria for evaluating the rough sketch are implicit.

In this paper, we present a quantitative evaluation method for the preliminary layout represented as a rough sketch along with a newly developed design support tool.

List of Symbols Used

- a : linear discriminant function factor
 C : design case vector
 d : mahalanobis distance
 f : similarity
 F : F -value
 h : probabilistic representation of d
 H : composition ratio representation of h
 p : pattern attribute
 P : pattern attribute vector
 S : sum of deviation squares-sum of products matrix
 S : sum of deviation squares
 t : t -value
 u : x -component of velocity vector
 v : y -component of velocity vector
 V : velocity vector
 W : complex potential
 w : variance-covariance matrix
 z : complex coordinate
 Z : linear discriminant function
 α : significance level
 ϕ : velocity potential
 χ : χ -value
 ψ : stream function

Subscripts

- g : actual results of success of layout ($g=1$: success, 0 : failure)
 i : component pattern attribute number ($i, i'=1, 2, \dots, I$)
 j : air flow pattern attribute number ($j, j'=1, 2, \dots, J$)
 k : mesh number ($k=1, 2, \dots, K$)
 m : design case number ($m=1, 2, \dots, M$)
 q, r : similarity number ($q, r=1, 2, \dots, s$)

2. Description of Past Design Cases

2.1 Similarity using pattern attribute vectors

One of the requirements of the forced-convection cooling design is to allow a well-balanced flow of air according to the internal components. In other words, the relation between the pattern of the component's attributes—including information on its shape and layout—and air flow pattern must be satisfied.

To describe this relation, a two-dimensional (2-

Fig. 2 Representation of cross section by pattern attribute

D) cross section of the electronic system is divided by rectangular meshes (Fig. 2). First, we define a pattern attribute vector for the internal components as in Eq. (1). The vector is constructed using pattern attribute values p_{ik} .

$$P_i = [p_{i1}, \dots, p_{ik}, \dots, p_{iK}] \quad (1)$$

A pattern attribute vector for air flow pattern P_j is also defined in a similar manner. Next, a similarity between P_i and P_j can be written in the form

$$f_{ij} = \frac{(P_i \cdot P_j)}{(\|P_i\| \cdot \|P_j\|)}, \quad (2)$$

where

$$\|P_i\| = \sqrt{\sum_{k=1}^K p_{ik}^2} \quad (3)$$

and $\|P_j\|$ is also written in a similar manner.

2.2 Pattern attribute

In this subsection, we explain some attributes and their mesh values. The pattern attributes for the internal components include the heat-resistance level ($i=1$), critical level ($i=2$), heat dissipation density ($i=3$), and volume porosity ($i=4$). These attributes are selected because they are important considerations in actual cooling design work.

• **Heat-resistance level**: Very strong, strong, weak and very weak heat-resistance are given values of 1 to 4, respectively. A mesh containing no component is given a value of zero.

• **Critical level**: Minimum, slight, serious and fatal are given values of 1 to 4, respectively. A mesh containing no component is given a value of zero. The critical levels are defined by failure mode and effects analysis (FMEA)⁽¹⁾.

• **Heat dissipation density**: This refers to a component's heating value divided by the number of meshes it occupies on a 2-D cross section, and represents the average heat dissipation density of the component.

• **Volume porosity**: This refers to the fluid occupation ratio⁽²⁾. The volume porosity is zero for a solid object and one for a filled fluid field.

The pattern attributes for air flow are the velocity potential ($j=1$) and stream function ($j=2$).

• **Velocity potential and stream function:** The information on air flow is expressed as the number of typical streamlines in a rough sketch (e.g. Fig. 1). The streamlines enable the visualization of essential information including air compression distribution and velocity distribution. Detailed information related to the P-Q property of a fan and wall friction is not treated in the preliminary design. Air flow is treated as a 2-D potential flow in an ideal fluid. For the complex coordinates $z = x + iy$, the relationship between the conjugate complex velocity $u - iv$ and complex potential $W(z) = \phi(x, y) + i\psi(x, y)$ to the velocity vector $V(u, v)$ is given by

$$\frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y}, \quad \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x},$$

$$\frac{dW}{dz} = \frac{\partial W}{\partial x} = \frac{\partial \phi}{\partial x} + i \frac{\partial \psi}{\partial x} = u - iv. \quad (4)$$

The air pressure distribution is expressed by the velocity potential $\phi(x, y)$. Likewise, the air velocity distribution is expressed by the stream function $\psi(x, y)$. The velocity potential and stream function in a 2-D cross section are calculated by summing the basic complex potentials of the sink, source and dipole. The inner-wall or guided-board is modeled as a vortex using a singular point solution. These calculated values of the velocity potential and stream function are given to each mesh.

Note that the velocity potential and stream function values can be positive or negative. Since the similarity expressed by Eq. (2) is a normalized scalar product between P_i and P_j , P_i and P_j have to be in the same quadrant. Here, the minimum values of the calculated velocity potential and stream function for each mesh are regarded as zero, and the other mesh values are adjusted accordingly. Figure 3 illustrates the similarity calculation.

2.3 Design case-base

Using similarity and actual results, the design case vector is written in the form

$$C^m = [f_{11}^m, \dots, f_{ij}^m, \dots, f_{ij}^m, g^m] \quad (5)$$

and the design case-base which describes all the design cases is given by

$$C = [C^1, \dots, C^m, \dots, C^M]^T. \quad (6)$$

3. Evaluating Function Based on Distance

In this chapter, we postulate that—(1) a skilled engineer evaluates a new solution using distance as the main criterion for comparison with past design cases, and (2) the success and failure cases can both be represented by normal population distributions with equal variance. On the basis of these assumptions, an evaluating function for a preliminary layout is proposed using the mahalanobis distance⁽³⁾ from past design cases. The mahalanobis distance is chosen

because it is based on a normal probabilistic density function.

First, similarities f_{ij} that are correlated closely with the actual results of success g are selected using variance analysis⁽⁴⁾ on f_{ij} and g (Appendix 1). Next, we let the selected f_{ij} be predictor variables and the g be the criterion variable, and then we calculate the linear discriminant function for selecting non-multicollinear parameters (Appendix 2). Using these statistically selected similarities, the mahalanobis distance $d_{(1)}$ and $d_{(0)}$ can be calculated from the success cases and failure cases. $d_{(1)}$ is given by

$$d_{(1)}^2 = \sum_{q=1}^S \sum_{r=1}^S (f_q - \bar{f}_q^{(1)}) w_{qr}^{-1} (f_r - \bar{f}_r^{(1)}) \quad (7)$$

and $d_{(0)}$ can also be expressed in a similar manner. Here subscripts q, r are similarity numbers for the selected similarities,

$$\bar{f}_q^{(1)} = \frac{\sum_{m(1)=1}^{M(1)} f_q^{m(1)}}{M(1)}, \quad (8)$$

Fig. 3 Schematic of similarity calculation

Fig. 4 Model of preliminary layout making process

w_{qr}^{-1} is a q, r -element of the inverse matrix of the pooled variance-covariance matrix w , and w_{qr} is given by

$$w_{qr} = \frac{S_{qr}^{(0)} + S_{qr}^{(1)}}{M-2}. \quad (9)$$

Here $S_{qr}^{(1)}$ is a q, r -element of the sum of deviation squares-sum of products matrix for success cases and is written in the form

$$S_{qr}^{(1)} = \sum_{m(1)=1}^{M(1)} (f_q^{m(1)} - \bar{f}_q^{(1)})(f_r^{m(1)} - \bar{f}_r^{(1)}). \quad (10)$$

$S_{qr}^{(0)}$ is also written in a similar manner. Note that the pooled variance-covariance matrix w is based on the assumption of equal variance for the populations of the success and failure cases. Thus, a test of equal variance is needed (Appendix 3).

Here, since the mahalanobis distance is essentially a probabilistic distance, $d_{(1)}$ and $d_{(0)}$ can be converted to probabilistic representations $h_{(1)}$ and $h_{(0)}$, respectively, where

$$h_{(1)} = \frac{\exp(-0.5d_{(1)}^2)}{(2\pi)^{s/2}\sqrt{|w|}}, \quad (11)$$

and $h_{(0)}$ is also written in a similar manner. Thus, the evaluating function for the preliminary layout is given

by

$$H_{(1)} = \frac{100h_{(1)}}{h_{(1)} + h_{(0)}}. \quad (12)$$

This evaluating function predicts and evaluates the probability of success of the new layout solution based on past cases. The above is outlined in Fig. 4(a).

4. Design Support Tool

4.1 Calculation of evaluating function

A total of 23 cases (14 success cases and 9 failure cases) were sampled, and the design case-base was made in the form of Eq. (6). Figure 5 illustrates an example of pattern attribute representation for a 2-D cross section. Table 1 shows the contents of the design case-base. First, variance analysis was executed on the data of Table 1. Then similarities f_{12} , f_{22} and f_{32} were selected as correlating closely with g (Table 2). Next, the linear discriminant function was calculated, and f_{22} and f_{32} were selected as non-multicollinear parameters (Table 3). The discriminant ratio of the evaluating function (Eq. (12)) using f_{22} and f_{32} was 78%.

Heat-resistance level(i=1)

3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3
4	4	4	4	1	1	1	1
4	4	4	4	1	1	1	1
4	4	4	4	1	1	1	1
3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3

Criticality level(i=2)

4	4	4	4	4	4	4	4
4	4	4	4	4	4	4	4
4	4	4	4	1	1	1	1
4	4	4	4	1	1	1	1
4	4	4	4	1	1	1	1
3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3
3	3	3	3	3	3	3	3

Heat dissipation density(i=3)

1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875
1.875	1.875	1.875	1.875	1.875	1.875	1.875	1.875
0.250	0.250	0.250	0.250	0.008	0.008	0.008	0.008
0.250	0.250	0.250	0.250	0.008	0.008	0.008	0.008
0.250	0.250	0.250	0.250	0.008	0.008	0.008	0.008
0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200

Volume porosity(i=4)

0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7

Velocity potential(j=1)

2.067	2.523	3.204	4.734	4.682	3.029	2.301	1.801
2.004	2.359	2.851	3.387	3.342	2.720	2.145	1.620
1.892	2.135	2.398	2.589	2.547	2.273	1.921	1.579
1.696	1.856	1.980	2.047	2.011	1.872	1.677	1.465
1.449	1.536	1.576	1.586	1.558	1.491	1.401	1.286
1.164	1.172	1.146	1.120	1.098	1.081	1.068	1.033
0.850	0.754	0.661	0.606	0.589	0.611	0.675	0.748
0.529	0.251	0.089	0.013	0.000	0.051	0.190	0.444

Stream function(j=2)

0.259	0.078	0.000	0.084	3.599	3.626	3.485	3.258
0.694	0.648	0.800	1.362	2.359	2.908	3.057	3.058
0.917	1.003	1.205	1.580	2.054	2.415	2.586	2.594
1.109	1.244	1.418	1.651	1.910	2.127	2.263	2.327
1.312	1.442	1.562	1.688	1.815	1.927	2.017	2.101
1.538	1.648	1.695	1.721	1.738	1.754	1.780	1.843
1.878	1.901	1.848	1.761	1.665	1.572	1.507	1.515
2.306	2.231	2.028	1.811	1.589	1.368	1.160	1.080

Table 1 Contents of design case-base

Case Number	f11	f21	f31	f41	f12	f22	f32	f42	g
1	0.9313	0.9327	0.6476	0.7402	0.7379	0.7382	0.5041	0.6768	1
2	0.7789	0.8129	0.8033	0.4319	0.8092	0.7797	0.6109	0.7071	1
3	0.7033	0.7264	0.7047	0.8648	0.5923	0.6031	0.5910	0.9224	1
4	0.3712	0.3450	0.2893	0.7445	0.6258	0.5989	0.5798	0.6269	1
5	0.6260	0.6041	0.5532	0.7473	0.6023	0.5670	0.5280	0.8325	1
6	0.7229	0.7621	0.7511	0.8538	0.6630	0.6424	0.5585	0.7306	1
7	0.5840	0.5248	0.5711	0.8551	0.5764	0.5474	0.6558	0.7306	1
8	0.8456	0.2031	0.5119	0.8266	0.8106	0.8049	0.7285	0.6858	1
9	0.5786	0.5818	0.5400	0.8824	0.6384	0.5717	0.4562	0.7594	1
10	0.5706	0.5287	0.3159	0.7287	0.5665	0.5077	0.3249	0.6931	1
11	0.4828	0.4570	0.4899	0.8768	0.6112	0.5404	0.7194	0.8522	1
12	0.7837	0.7259	0.7637	0.7782	0.7112	0.6812	0.6528	0.8797	1
13	0.4677	0.4735	0.4655	0.7161	0.5779	0.5570	0.5892	0.7467	1
14	0.4975	0.4902	0.5031	0.7696	0.6464	0.4977	0.6972	0.6387	1
15	0.4584	0.4064	0.3804	0.8369	0.1924	0.1672	0.1327	0.4583	0
16	0.5678	0.5634	0.5163	0.7813	0.6306	0.6268	0.5095	0.7277	0
17	0.5151	0.5016	0.4509	0.8861	0.5153	0.4987	0.4396	0.8431	0
18	0.5997	0.5224	0.3995	0.8082	0.5939	0.5325	0.4256	0.8790	0
19	0.5729	0.5053	0.3939	0.8560	0.5558	0.5096	0.4209	0.7897	0
20	0.4829	0.5193	0.4676	0.7728	0.6397	0.6096	0.4357	0.8079	0
21	0.5051	0.5326	0.4694	0.7889	0.6515	0.6240	0.4519	0.8042	0
22	0.4454	0.3961	0.4745	0.7472	0.5695	0.4985	0.6806	0.8397	0
23	0.6725	0.6177	0.6539	0.8471	0.4192	0.2584	0.5319	0.8413	0

Fig. 5 Example of pattern attribute

4.2 Design support procedure

If an evaluated function is calculated, the preliminary layout decision process can be modeled by a generate-test process. The preliminary layout decision support procedure is as follows [Fig. 4 (b)].

Step a'. An engineer inputs pattern attributes for internal components.

Step b'. The engineer places each internal component in a system.

Step a. The pattern attributes for internal components are converted to pattern attribute vectors by the tool.

Step c'. The engineer places the system's sink, source and dipole as a guiding-board.

Step b. The pattern attributes for air flow are calculated and converted to a pattern attribute vector by the tool.

Step c. The similarity of the new preliminary layout is calculated by the tool.

Step d'. The evaluation is executed and the result is expressed by the tool.

Step e'. The engineer refers to the result of the evaluation and decides whether or not it is acceptable.

4.3 Implementation

The procedure shown in Fig. 4 (b) was implemented in C using a Sun SPARCstation. X Window was used as the human interface. PEX was used as a 3-D graphics library, and Motif was used as the X tool kit for GUI development. The advantage of this design support tool is that it can evaluate and express results quickly. The other functions of this tool are as follows.

Table 2 Result of variance analysis

fij	F-value	F>4.325 ?
f11	3.230	No
f21	1.259	No
f31	2.938	No
f41	1.042	No
f12	6.998	Yes
f22	6.345	Yes
f32	6.786	Yes
f42	0.351	No

where $F(1, 21, 0.05) = 4.325$

Table 3 Check of multicollinearity

fij	aij	fij(1)-fij(0)	Multicollinearity?
f12	-2.120	0.125	Yes
f22	7.673	0.136	No
f32	7.019	0.138	No

- The tool can display a layout at the halfway point, allowing the engineer to transcribe it if necessary.
- It can generate and show the streamlines using complex potentials, allowing the engineer to understand the flow patterns under evaluation.
- It can share 2-D and 3-D layout information, allowing 2-D cross sections to be generated from a 3-D representation of the solution.

Figure 6(a) is a screen dump for components input from this tool. Figure 6(b) is a screen dump showing the evaluation result. The engineer inputs information about the components and air flow, enters the points of the 2-D cross section, and makes the tool perform an evaluation for the new preliminary layout. This example shows that the tool evaluates the particular 2-D cross section to have a 91% probability of being successful. From the evaluation, the engineer

(a) Example of input data

(b) Calculated result

Fig. 6 Example of design support tool

can decide the final layout. In the other examples also, the evaluation results were found to be valid.

These results indicate that the proposed evaluating function will be useful in deciding the preliminary layout.

5. Discussion

The calculations for the proposed evaluating function can be performed faster than calculations for numerical simulation. We consider the proposed method to be practical for use in a trial and error process because it shortens the calculation time. Note that the evaluating function is calculated by statistical methods without domain knowledge. Hence, this study can be applied to problems which require the relation between pattern attributes to be satisfied. The validity of the evaluation result is assured statistically, but not physically. This study, is therefore particularly useful in cases where information for numerical simulation is inadequate but there is enough data for past cases.

6. Conclusions and Future Work

The results of this study can be summarized as follows.

- A description of design cases using similarity for pattern attribute vectors was proposed.
- An evaluating function based on distance was

proposed, and a calculation method for the evaluating function was demonstrated.

- A design support tool was developed, and its usefulness was shown.
- The practicality and applicability of this study were discussed.

The required future work is summarized below.

- To update the evaluating function automatically with the tool using the design cases.
- To construct a more practical tool by combining electrical and mechanical constraint conditions.

Appendix 1

Between-classes sum of deviation squares S_1 and within classes sum of deviation squares S_2 are defined by

$$S_1 = \sum_{g=0}^1 M(g) (\bar{f}_{ij}^{(g)} - \bar{f}_{ij})^2 \quad (13)$$

and

$$S_2 = \sum_{g=0}^1 \sum_{m(g)=1}^{M(g)} (f_{ij}^{m(g)} - \bar{f}_{ij}^{(g)})^2, \quad (14)$$

where $M = M(0) + M(1)$, and is the mean value of f_{ij} for the total design cases (success and failure). Here, the F -value is given by

$$F = \frac{[S_1(M-2)]}{S_2}, \quad (15)$$

and f_{ij} values which satisfy the following F -test equation are selected.

$$F \geq F(1, M-2, \alpha); \alpha=0.05. \quad (16)$$

Appendix 2

The linear discriminant function is written in the form

$$Z = a_0 + a_1 f_1 + \dots + a_q f_q + \dots + a_s f_s, \quad (17)$$

where $a_1 \sim a_s$ can be calculated by solving Eq. (18).

$$\mathbf{w} \begin{bmatrix} a_1 \\ \vdots \\ a_q \\ \vdots \\ a_s \end{bmatrix} = \begin{bmatrix} \bar{f}_1^{(1)} - \bar{f}_1^{(0)} \\ \vdots \\ \bar{f}_q^{(1)} - \bar{f}_q^{(0)} \\ \vdots \\ \bar{f}_s^{(1)} - \bar{f}_s^{(0)} \end{bmatrix} \quad (18)$$

Here, if Eq. (19) is satisfied, then f_q cannot be used for calculation of the mahalanobis distance because multicollinearity occurs.

$$a_q (\bar{f}_q^{(1)} - \bar{f}_q^{(0)}) < 0 \quad (19)$$

Appendix 3

The χ^2 value used in the M-test is given by

$$\chi^2 = \left(1 - \frac{2s^2 + 3s - 1}{6(s+1)} \left\{ \frac{1}{[M(0)-1]} + \frac{1}{[M(1)-1]} + \frac{1}{[M-2]} \right\} \right) \cdot \log \left(\frac{|S'|^{M-2}}{|S^{(0)}|^{M(0)-1} |S^{(1)}|^{M(1)-1}} \right), \quad (20)$$

where S' is the weighted mean of $S^{(1)}$ and $S^{(2)}$. If Eq. (21) is satisfied, then equal variance is assured.

$$\chi^2 < \chi^2(3, \alpha); \alpha=0.05 \quad (21)$$

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