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Determination of Pinning Parameters in Flux Creep-Flow Model for E - J characteristics of High Temperature Superconductors by using Differential Evolution

E S Otabe¹, T Taguchi¹, Y Tsuruda¹ and R Funaki²

¹ Department of Computer Science and Electronics, Kyushu Institute of Technology, 680 – 4 Kawazu, Iizuka, Fukuoka, 820 – 8502, Japan

² Department of Electrical Engineering, Kyushu University, 744 Motoooka Nishi-ku, Fukuoka, 819 – 0395, Japan

otabe@cse.kyutech.ac.jp

Abstract. The pinning parameters such as strength of pinning force, temperature dependence of pinning force and so on using in flux creep-flow model to explain electric field vs current density (E - J) characteristics were determined by Differential Evolution (DE). DE is one of the methods in Evolutionary Computation (EC) to find an optimization of a problem. First, a model data of E - J characteristics in which the pinning parameters were given was prepared, and it was confirmed that DE can find the given pinning parameters from the model data. Then, DE and mesh method were used to determine the pinning parameters in experimental E - J characteristics of $\text{GdBa}_2\text{CuO}_{7-\delta}$ high temperature superconductor. In mesh method, the all combinations of pinning parameters with constant interval for each parameter are calculated, and best set of pinning parameters is selected. It was found that DE shows better performance than mesh method in terms of calculation time and accuracy for determining pinning parameters.

1. Introduction

Electric field vs current density (E - J) characteristics of high temperature superconductor (HTS) are important for many kind of applications using superconductor, since other characteristics such as magnetic field dependence of critical current density, irreversibility field are obtained from E - J characteristics. It is well known that flux creep-flow model can explain E - J characteristics of HTS by using several pinning parameters such as the strength of pinning force, the temperature dependence of pinning force and so on, since the flux creep phenomenon due to thermal agitation is severe at high temperatures [1]. However, it is difficult to determine the pinning parameter to fit the experimental and calculated results, since the number of fitting parameters is 4 to 5. In our previous work, Genetic Algorithm (GA) was used to determine the pinning parameters of the flux creep-flow model [2]. It was found that GA was effective to determine the parameters. However, since GA has complicated procedure for calculation, the calculation time tends to long and the computer program is difficult. In the present study, we use Differential Evolution (DE) to determine the pinning parameters. DE is one of the methods in Evolutionary Computation (EC) to find an optimization of a problem, and it was



proposed by R. Storn and K. Price in 1995 [3, 4]. In Ref. 4, DE is compared with several optimization-search programs including GA and it is found that DE shows better performance in many kinds of benchmark tests. DE is known to be able to be applied many kinds of problem for searching optimum condition. Recently, it is shown that the modified DE is effective for solving combinatorial optimization problems [5, 6].

In this study, several data sets of E - J characteristics are used, and the pinning parameters of the flux creep-flow model are deduced by DE. We discuss the advantage of using DE by comparing with other solving method.

2. Calculation

It is well known that the electric field vs current density (E - J) characteristics of high temperature superconductors can be explained by the flux creep-flow model [1]. In this model, several pinning parameters have to be determined. The strength of flux pinning, A , temperature and magnetic field dependences of critical current density for the case of virtual flux-creep free, m and γ are assumed in the equation of virtual critical current density, J_{c0} , as

$$J_{c0} = A \left(1 - \frac{T}{T_c}\right)^m B^{\gamma-1} \left(1 - \frac{B}{B_{c2}}\right)^2. \quad (1)$$

In practical superconductors, the flux pinning strength is known to be widely distributed and is expressed as

$$f(A) = K \exp \left[-\frac{(\log A - \log A_m)^2}{2\sigma^2} \right], \quad (2)$$

where A_m is the most probable value of A , σ^2 is a parameter representing a distribution width and K is a normalization constant. In this study, the pinning parameters, A_m , σ^2 , m and γ are determined in terms of fitting of the theoretical and experimental results by using Differential Evolution (DE).

In DE, after initialize individuals, for each individual \mathbf{x} , evolution is determined by so called mutant vector \mathbf{M} calculated from randomly picked up other individuals \mathbf{x}_1 , \mathbf{x}_2 , \mathbf{x}_3 given by

$$\mathbf{M} = \mathbf{x}_1 + F(\mathbf{x}_2 - \mathbf{x}_3), \quad (3)$$

where $0 < F < 1$ is a constant representing the scale factor of vector length. Then trial vector \mathbf{y} is generated by crossing of \mathbf{x} and \mathbf{M} . Finally, \mathbf{x} is compared with \mathbf{y} and if random number is smaller than CR and \mathbf{y} is better than \mathbf{x} , \mathbf{x} is replaced and evolved as \mathbf{y} , where CR is crossover probability. The evaluation value d in the present study is given by

$$d = \frac{1}{N} \sum [\log(E_{\text{exp}}) - \log(E_{\text{theo}})]^2 \quad (4)$$

where E_{exp} and E_{theo} are experimental and theoretical results of electric field, N is the number of sampling. Further information is in Refs. [1, 2]. In the above procedure, it is found that the all individuals move to better positions than one generation before. In present study, \mathbf{x} is the vector consisted from 4 pinning parameters, A_m , σ^2 , m and γ . The number of individuals is 30, and the number of generations is up to 20000.

First, DE is confirmed with using a model data of E - J in which the pinning parameters are given. Then an experimental data of E - J of $\text{GdBa}_2\text{CuO}_{7-\delta}$ (Gd-123) coated conductor of 1.56 μm thickness at 20 and 40 K is used and pinning parameters are determined by DE. For comparison of DE, the mesh method is used. In mesh method, the all combinations of pinning parameters with constant interval for each parameter are calculated, and best set of pinning parameters is selected. In present study, $11^4 = 14641$ sets of parameters are calculated, i.e., each parameter is divided in 11 cases.

3. Results and discussion

First, DE is used to deduce for the model data of E - J and tries to find the given pinning parameters. It is confirmed that DE can deduce the given parameters. Then, DE is used to deduce the pinning parameters for experimental data of Gd-123 superconductor. Figure 1 shows the comparison of E - J of

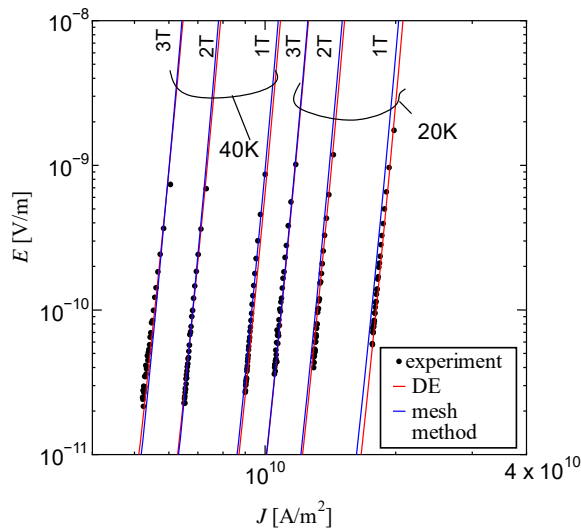


Figure 1. Experimental result of E-J characteristics and theoretical results by pinning parameters determined by DE and mesh method.

Table 1. Comparison of pinning parameters, evaluation value d and calculation time for two methods.

	mesh method	Differential Evolution
$\log_{10}(A_m)$	11.00	11.15
σ	1.00×10^{-2}	1.12×10^{-3}
γ	6.40×10^{-1}	6.31×10^{-1}
m	3.60	3.70
d	4.18×10^{-2}	9.19×10^{-3}
Time [s]	232	79

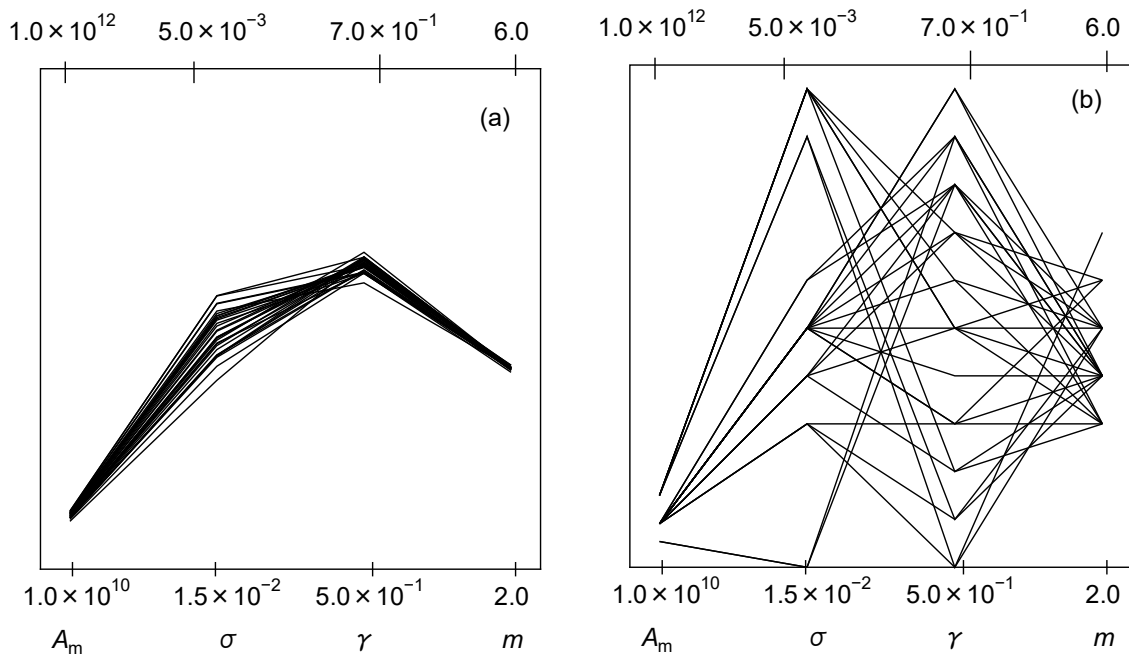


Figure 2. Best 30 pinning parameter sets of (a) DE and (b) mesh method. For example, A_m is in the range of $1.0 \times 10^{10} - 1.0 \times 10^{12}$ from lower abscissa to upper abscissa. Solid line connects the set of pinning parameters.

experimental result, prediction by flux-creep flow model using pinning parameters determined by DE and mesh method. Table 1 lists the pinning parameter determined by two methods and the evaluation value d and time for calculation. The scale factor of vector length $F = 1$ and crossover probability $CR = 0.5$ are used in the calculation of DE. It is found that determination of parameters by DE is better than that of the mesh method. Since pinning parameters can be set more flexible in DE than the mesh method, d is smaller in DE.

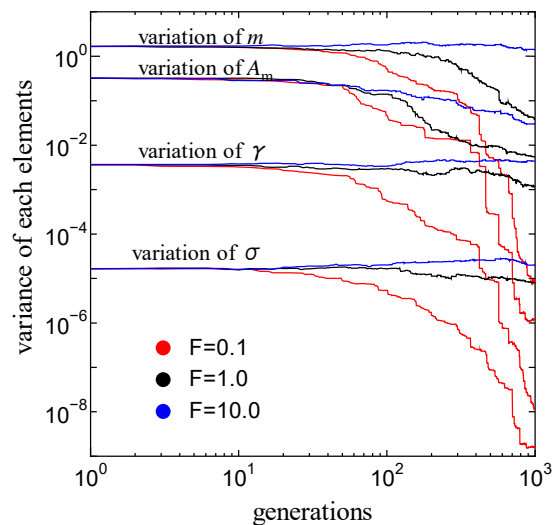


Figure 3. Generation dependence of variance of each pinning parameter for various scale factor of vector length F .

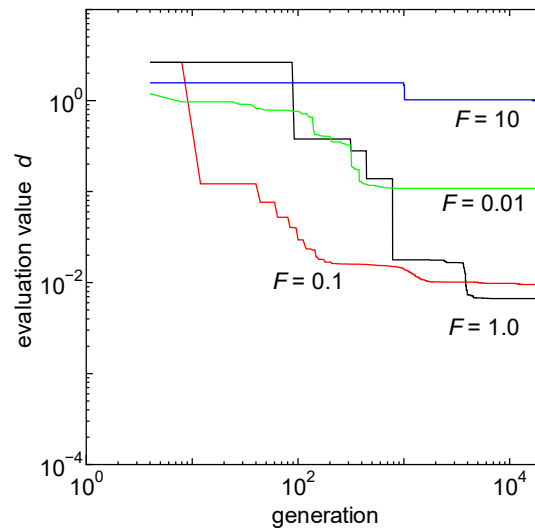


Figure 4. Generation dependence of evaluation value d for various scale factor of vector length F .

In figure 2 (a) and (b), the best 30 sets of pinning parameters by DE and mesh method are shown. The sets are almost same in DE, i.e., after evolution all sets move toward almost same area where d is enough small. On the other hand, the sets of parameters in the mesh method are distributed widely. This means that there are many local minimum of d in addition of optimum condition. Therefore, it is expected to use DE to solve optimization problems when using superconductors such as designs of superconducting motor and magnet.

Figure 3 shows variance of each parameter as a function of generation. It is found that the variance of each parameter decreases as increasing generation, as well as decreasing the scale factor of vector length F . It is also confirmed that the variance of each parameter is smallest for the case of $F = 0.01$. However, this does not mean that the obtained pinning parameters are best. That is, the individuals does not move from the local minimum area due to small value of $F = 0.01$, and the best pinning parameters are obtained for the case of $F = 1$.

Finally, generation dependence of evaluation value d for various value of F is shown in figure 4. The evaluation value monotonically decreases as increasing generation for each value of F . It is found that the case of $F = 1$ reaches the best value of d .

4. Conclusion

In the present study, the four pinning parameters of the flux creep-flow model to explain E - J characteristics in superconductors were determined by Differential Evolution (DE), which is one of the method of Evolutionary Computation. And the results were compared by the mesh method. In mesh method, the all combinations of pinning parameters with constant interval for each parameter are calculated, and best set of pinning parameters is selected. It is found that the evaluation value of DE is better than the mesh method, and the calculation time is shorter in DE than the mesh method. Therefore, it is useful to use DE for determining the pinning parameters of the flux creep-flow model for E - J characteristics in superconductors.

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244

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