Maxwell

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(1. , 235000 ;2. , 221116)

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Maxwell , , ,
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:Maxwell ; ;
:O241.82 :A

Ritz-Galerkin , :
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。 2015 , [1] ,
、 Sine-Gordon , 。 2016
, [2] Chebyshev-Galerkin ,
, L_2 。 2017 , [3]
Cahn-Hilliard 。 2018 , [4]
Legendre , Legendre-Galerkin-Chebyshev , Crank-Nicolson ,
Burgers - Burgers
Galerkin , Maxwell [5]

$$\begin{cases} \mu\dfrac{\partial \widetilde{H}^x}{\partial \widetilde{t}}=-\dfrac{\partial \widetilde{H}^z}{\partial \widetilde{y}} \\[2mm] \mu\dfrac{\partial \widetilde{H}^y}{\partial \widetilde{t}}=\dfrac{\partial \widetilde{E}^z}{\partial \widetilde{x}} \\[2mm] \varepsilon\dfrac{\partial \widetilde{E}^z}{\partial \widetilde{t}}=\dfrac{\partial \widetilde{H}^y}{\partial \widetilde{x}}-\dfrac{\partial \widetilde{H}^x}{\partial \widetilde{y}} \end{cases} \tag{1}$$

:$\mu(\widetilde{x})$,$\varepsilon(\widetilde{x})$,$(\widetilde{H}^x,\widetilde{H}^y)$,$\widetilde{E}^z$, $(\widetilde{x},\widetilde{y},\widetilde{t})$, $\mu=\mu_0$,

$\varepsilon=\varepsilon_0$, $c_0=\dfrac{1}{\sqrt{\varepsilon_0\mu_0}}\cong 8.33\times10^5$ m/h, $t=\dfrac{c_0\widetilde{t}}{L}$,$x=\dfrac{\widetilde{x}}{L}$,$H=\dfrac{H}{H_0}$,$E^z=(Z_0)^{-1}\dfrac{\widetilde{E}^z}{H_0}$, (1)

$$\dfrac{\partial H^x}{\partial t}=-\dfrac{\partial E^z}{\partial y}, \dfrac{\partial H^y}{\partial t}=-\dfrac{\partial E^z}{\partial x}, \dfrac{\partial E^z}{\partial t}=\dfrac{\partial H^y}{\partial x}-\dfrac{\partial H^x}{\partial x}$$

:H_0 ,$H_0=\sqrt{\dfrac{\mu_0}{\varepsilon_0}}\cong 120\pi$;$L$ 。

Maxwell 　　[5]

$$\varepsilon\frac{\partial E}{\partial t}-\nabla\times H=0,\quad \mu\frac{\partial H}{\partial t}+\nabla\times E=0 \tag{2}$$

:$E=(E^x,E^y,E^z)$　　　　　　，$H=(H^x,H^y,H^z)$　　　　　，　　　　　，[6]

$$-[\hat{n}\times H-(\hat{n}\times H)^*]=-\frac{1}{2\{\{Z\}\}}\hat{n}\times[Z^+(H^--H^+)-\alpha\hat{n}\times(E^--E^+)],$$

$$[\hat{n}\times E-(\hat{n}\times E)^*]=-\frac{1}{2\{\{Y\}\}}\hat{n}\times[Y^+(E^--E^+)+\alpha\hat{n}\times(H^--H^+)]。$$

:$Z^{\pm}=\dfrac{1}{Y^{\pm}}=\sqrt{\dfrac{\mu^{\pm}}{\varepsilon^{\pm}}}$，$\alpha\in[0,1]$，　　$\alpha=1$　　　　　　　，　　$Z=Y=1$　　，　（1）

$$\hat{n}\cdot(F-F^*)=\frac{1}{2}\begin{vmatrix}\hat{n}_y[E^z]+\alpha(\hat{n}_x[H]-[H^x]\\-\hat{n}_x[E^z]+\alpha(\hat{n}_y[H]-[H^y]\\\hat{n}_y[H^x]+\hat{n}_x[H^y]-\alpha[E]\end{vmatrix}$$

:$H=(H^x,H^y)$，　$[q]=q^--q^+=\hat{n}\cdot[q]$。

$$\frac{\mathrm{d}H_h^x}{\mathrm{d}t}=-D_yE_h^z+\frac{1}{2}(JM)^{-1}\int_{\partial D^k}(\hat{n}_y[E_h^z]+\alpha(\hat{n}_x[H_h]-[H_h^x]))l(x)\mathrm{d}x$$

$$\frac{\mathrm{d}H_h^y}{\mathrm{d}t}=D_xE_h^z+\frac{1}{2}(JM)^{-1}\int_{\partial D^k}(-\hat{n}_x[E_h^z]+\alpha(\hat{n}_y[H_h]-[H_h^y]))l(x)\mathrm{d}x \tag{3}$$

$$\frac{\mathrm{d}E_h^z}{\mathrm{d}t}=D_xH_h^y-D_yH_h^x+\frac{1}{2}(JM)^{-1}\int_{\partial D^k}(\hat{n}_y[H_h^x]-\hat{n}_x[H_h^y]-\alpha[E_h^z])l(x)\mathrm{d}x$$

:(H_h^x,H_h^y,E_h^z)　　　　　　。

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Maxwell

$$\left.\begin{array}{l}i\omega\widetilde{H}^x=-\dfrac{\partial\widetilde{E}^z}{\partial y}\\[2mm]i\omega\widetilde{H}^y=-\dfrac{\partial\widetilde{E}^z}{\partial x}\\[2mm]i\omega\widetilde{E}^z=\dfrac{\partial\widetilde{H}^y}{\partial x}-\dfrac{\partial\widetilde{H}^x}{\partial y}\end{array}\right\} \tag{4}$$

$$0=\frac{\partial\widetilde{H}^x}{\partial x}+\frac{\partial\widetilde{H}^y}{\partial y}$$

$$\hat{n}\cdot\widetilde{H}=0,\widetilde{E}^z=0$$

$\hat{n}\times[\widetilde{E}]=0,\hat{n}\times[\widetilde{H}]=0$。　　　:$[u]=u^--u^+$　　　　　　，u^+　　　　，u^-　　　　　。（3）

，

$$\left.\begin{array}{l}i\omega\widetilde{H}_h^x=-D_y\widetilde{E}_h^z+\dfrac{M^{-1}}{2J}\int_{\partial D^k}(\hat{n}_y[\widetilde{E}_h^z]-\alpha[\widetilde{H}_h^n]\hat{n}_x-\beta[\widetilde{H}_h^\tau]\hat{n}_y)l(x)\mathrm{d}x\\[3mm]i\omega\widetilde{H}_h^y=D_y\widetilde{E}_h^z+\dfrac{M^{-1}}{2J}\int_{\partial D^k}(-\hat{n}_x[\widetilde{E}_h^z]-\alpha[\widetilde{H}_h^n]\hat{n}_y-\beta[\widetilde{H}_h^\tau]\hat{n}_x)l(x)\mathrm{d}x\\[3mm]i\omega\widetilde{E}_h^z=-D_y\widetilde{H}_h^x+D_x\widetilde{H}_h^y+\dfrac{M^{-1}}{2J}\int_{\partial D^k}(-\gamma[\widetilde{E}_h^z]+[\widetilde{H}_h^x]\hat{n}_y-[\widetilde{H}_h^y]\hat{n}_x)l(x)\mathrm{d}x\end{array}\right\} \tag{5}$$

$: \widetilde{H}^n = \widetilde{H}^x \hat{n}_x + \widetilde{H}^y \hat{n}_y$, $\widetilde{H}^\tau = \widetilde{H}^x \hat{n}_y - \widetilde{H}^y \hat{n}_x$ 。

$\omega = 0$, (H^x, H^y, H^z) , Lax−Fridrichs

$$0 = -D_y \widetilde{E}_h^z + \frac{M^{-1}}{2J} \int_{\partial D^k} (\hat{n}_y [\widetilde{E}_h^z] - \alpha [\widetilde{H}_h^n] \hat{n}_x - \beta [\widetilde{H}_h^\tau] \hat{n}_y) l(x) \mathrm{d}x$$

$$0 = D_y \widetilde{E}_h^z + \frac{M^{-1}}{2J} \int_{\partial D^k} (-\hat{n}_x [\widetilde{E}_h^z] - \alpha [\widetilde{H}_h^n] \hat{n}_y - \beta [\widetilde{H}_h^\tau] \hat{n}_x) l(x) \mathrm{d}x$$

$$0 = -D_y \widetilde{H}_h^x + D_x \widetilde{H}_h^y + \frac{M^{-1}}{2J} \int_{\partial D^k} (-\gamma [\widetilde{E}_h^z] + [\widetilde{H}_h^x] \hat{n}_y - [\widetilde{H}_h^y] \hat{n}_x) l(x) \mathrm{d}x$$

(6)

$(\widetilde{H}_h, \widetilde{E}_h^z)$ L^2 ,

$$0 = -\sum_k \gamma (([\widetilde{E}_h^z], [\widetilde{E}_h^z])_{\partial D^k} + \alpha([\widetilde{H}_h^n], [\widetilde{H}_h^n])_{\partial D^k} + \beta [\widetilde{H}_h^\tau], [\widetilde{H}_h^\tau])_{\partial D^k})$$

（5） , （4） [7−8] 、 [9−10] 、 Lax−Fridrichs , , , ,

$$\mathrm{Re}(i\omega) = \frac{\sum_k \oint_{\partial D} (\gamma ([\widetilde{E}_h^z]^z + \alpha([\widetilde{H}_h^n]^2 + \beta [\widetilde{H}_h^\tau]^2) \mathrm{d}x}{\| H_h^x \|_{\Omega,h}^2 + \| H_h^y \|_{\Omega,h}^2 + \| E_h^z \|_{\Omega,h}^2}$$

$: \alpha, \beta, \gamma$, L_2 ; $\alpha=0, \beta=1, \gamma=1$, ; $\alpha=1, \beta=0, \gamma=1$, ; $\alpha=1, \beta=1, \gamma=1$, Lax−Fridrichs 。

2

Maxwell , Maxwell

$$\nabla \times \nabla \times \widetilde{E} = \omega^2 \widetilde{E}$$

$\omega^2 = n^2 + m^2$, (m,n) , $\Omega \in [-1,1]^2$

, $\widetilde{E}$, [11] , 1 h 。
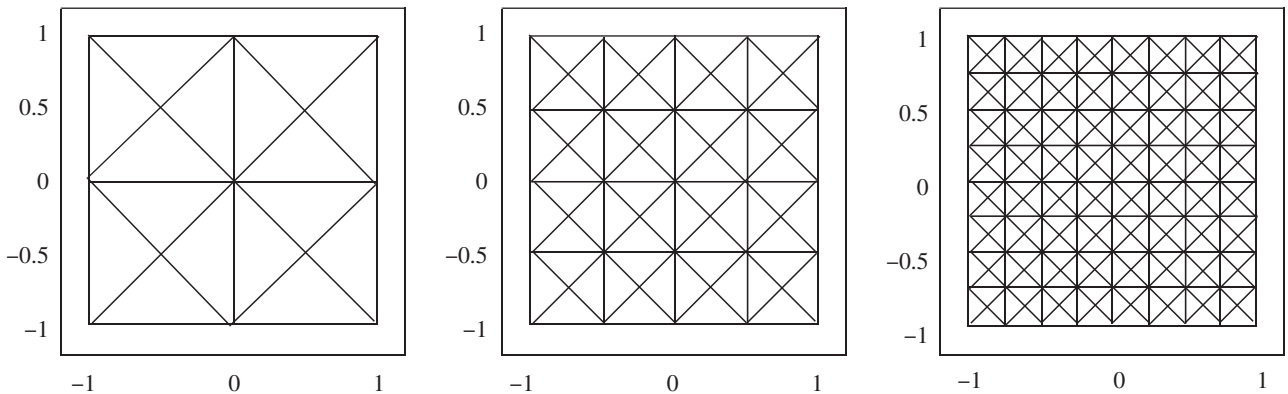

1
Fig.1 Staggered grid for calculating eigenvalue problems over metal square domains with ideal boundary conditions

, 、 Lax−Fridrichs ,

N , 。

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, $N+1$ $\{\psi_n(x)\}_{n=1}^{N_p} \left(N_p = \frac{(N+2)(N+3)}{2} \right)$ N

$$\varphi_n=\left(\frac{\partial\psi_n}{\partial y},-\frac{\partial\psi_n}{\partial x}\right)$$

$$\nabla\cdot\varphi_n=0,$$

$$\widetilde{H}^x=\sum_{n=2}^{N_p}\widetilde{H}_n\frac{\partial\psi_n}{\partial y},\quad\widetilde{H}^y=\sum_{n=2}^{N_p}-\widetilde{H}_n\frac{\partial\psi_n}{\partial x}$$

: $\widetilde{H}^n$ H ,H $(N+1)(N+4)/2$ 。

[12]。

1 MATLAB $N=3$ $N=5$,
$O(h^{2N+1})$ 。 2 , $N=3$ $O(h^{2N+1})$,
$N=5$ 。 3 $N=3$ $N=5$
, $O(h^{2N-1})$ 。 4
, $N=3$ $O(h^{2N-1})$, $N=5$ 。 5 Lax−
Fridrichs $N=3$ $N=5$, $O(h^{2N+1})$ 。 6
, $N=3$ $O(h^{2N+1})$,
$N=5$ 。

<div align="center">1 10</div>

Tab.1 Convergence for the first 10 eigenvalues of operator with an upwind flux

	N=3				N=5			
	h	h/2	h/4		h	h/2	h/4	
(1,1)	2.9e−06	1.1e−08	4.2e−11	8.0	8.2e−11	2.1e−14	5.8e−14	5.2
(1,2)	3.0e−04	1.2e−06	4.9e−09	7.9	9.4e−08	2.4e−14	5.8e−14	10.8
(1,3)	5.3e−03	3.2e−05	1.4e−07	7.6	9.8e−06	3.2e−09	8.3e−14	11.8
(1,4)	3.2e−02	3.5e−04	1.6e−06	7.1	9.8e−06	3.2e−09	8.3e−14	11.3
(2,1)	3.0e−04	1.2e−06	1.6e−06	7.9	9.8e−06	3.2e−09	8.3e−14	10.1
(2,2)	1.4e−04	4.6e−06	1.8e−08	6.4	5.9e−06	3.2e−09	8.3e−14	9.6
(2,3)	6.3e−03	4.4e−05	1.8e−08	7.5	5.9e−06	3.2e−09	8.3e−14	11.6
(3,1)	5.9e−03	3.2e−05	1.4e−07	7.7	1.0e−05	3.2e−09	8.6e−14	11.7
(3,2)	6.3e−03	4.4e−05	1.9e−07	7.5	1.1e−05	4.6e−09	1.3e−12	11.5
(4,1)	3.2e−02	3.5e−05	1.6e−07	7.1	2.0e−04	1.1e−07	1.3e−12	11.2

<div align="center">2 10</div>

Tab.2 Convergence for the first 10 eigenvalues of operator with upwind flux and locally divergence−free basis

	N=3				N=5			
	h	h/2	h/4		h	h/2	h/4	
(1,1)	3.5e−06	1.5e−08	6.2e−011	7.9	9.9e−11	1.6e−13	4.9e−12	2.2
(1,2)	3.0e−04	1.2e−06	4.6e−09	8.0	9.5e−08	2.2e−11	2.6e−13	9.2
(1,3)	5.5e−03	2.8e−05	9.5e−08	7.9	1.1e−05	3.2e−09	4.2e−12	10.7
(1,4)	5.0e−02	4.0e−04	1.2e−06	7.7	3.6e−04	1.4e−07	1.6e−11	12.2
(2,1)	3.0e−04	1.2e−06	4.6e−09	8.0	9.5e−08	2.3e−11	1.7e−12	7.9
(2,2)	7.4e−05	5.5e−06	2.6e−08	5.8	7.1e−08	1.7e−10	5.5e−12	6.8
(2,3)	6.6e−03	4.9e−05	2.3e−07	7.4	1.3e−05	5.5e−09	5.1e−12	10.6
(3,1)	7.3e−03	3.3e−05	1.0e−07	8.0	1.3e−05	3.5e−09	3.0e−11	9.4
(3,2)	6.6e−03	4.9e−05	2.3e−07	7.4	1.3e−05	5.5e−09	2.0e−11	9.7
(4,1)	5.0e−02	4.0e−04	1.2e−06	7.7	3.6e−04	1.4e−07	3.3e−11	11.7

3   **10**
Tab.3   Convergence for the first 10 eigenvalues of operator with a penalty flux

	N=3				N=5			
	h	$h/2$	$h/4$		h	$h/2$	$h/4$	
(1,1)	2.5e−05	5.7e−07	1.1e−08	5.6	9.3e−10	1.6e−12	3.3e−14	7.4
(1,2)	8.5e−04	1.7e−05	3.8e−07	5.6	3.8e−07	4.5e−10	7.1e−13	9.5
(1,3)	9.2e−03	1.3e−04	2.9e−06	5.8	1.7e−05	1.7e−08	2.5e−11	9.7
(1,4)	3.1e−02	8.7e−04	1.8e−05	5.4	1.4e−04	4.8e−07	5.6e−10	9.0
(2,1)	8.5e−04	1.7e−05	3.8e−07	5.6	3.8e−07	4.5e−010	7.8e−13	9.4
(2,2)	1.2e−03	6.4e−05	1.3e−06	4.9	5.9e−07	2.7e−09	3.8e−12	8.6
(2,3)	7.8e−03	2.5e−04	5.5e−06	5.2	1.6e−05	3.2e−08	4.7e−11	9.2
(3,1)	1.4e−02	2.2e−04	3.9e−06	5.9	4.6e−05	4.3e−08	4.2e−11	10.0
(3,2)	7.8e−03	2.5e−04	5.5e−06	5.2	1.6e−05	3.2e−08	4.7e−11	9.2
(4,1)	3.1e−02	8.7e−04	1.8e−05	5.4	1.4e−04	4.8e−07	5.6e−10	9.0

4   **10**
Tab.4   Convergence for the first 10 eigenvalues of operator with penalty flux and locally divergence−free basis

	N=3				N=5			
	h	$h/2$	$h/4$		h	$h/2$	$h/4$	
(1,1)	2.4e−05	4.8e−07	8.8e−09	5.7	9.3e−10	5.6e−13	7.2e−12	3.5
(1,2)	8.8e−04	1.6e−05	3.5e−07	5.6	3.3e−07	3.6e−10	4.9e−12	8.0
(1,3)	1.2e−02	1.1e−04	2.6e−06	6.0	2.7e−05	1.2e−08	1.9e−11	10.2
(1,4)	4.0e−02	8.4e−04	1.6e−05	5.6	2.9e−04	3.7e−07	3.4e−10	9.8
(2,1)	8.8e−04	1.6e−05	3.5e−07	5.6	3.3e−07	3.6e−10	1.5e−12	8.9
(2,2)	1.2e−03	6.2e−05	1.1e−06	5.0	5.9e−07	2.4e−09	1.7e−12	9.2
(2,3)	8.4e−03	2.4e−04	4.5e−06	5.4	1.3e−05	2.7e−08	1.1e−11	10.0
(3,1)	1.4e−02	2.0e−04	3.4e−06	6.0	3.4e−05	3.6e−08	3.8e−11	9.9
(3,2)	8.4e−03	2.4e−04	4.5e−06	5.4	1.3e−05	2.7e−08	4.7e−11	9.0
(4,1)	4.0e−02	8.4e−04	1.6e−05	5.6	2.9e−04	3.7e−07	3.5e−10	9.8

5   **Lax−Friedrichs**   **10**
Tab.5   Convergence for the first 10 eigenvalues of operator with Lax−Friedrichs flux

	N=3				N=5			
	h	$h/2$	$h/4$		h	$h/2$	$h/4$	
(1,1)	3.3e−06	1.9e−08	7.5e−11	7.7	1.0e−10	4.9e−14	5.3e−15	7.1
(1,2)	3.1e−04	1.5e−06	7.7e−09	7.6	7.5e−08	2.3e−11	3.7e−14	10.5
(1,3)	5.0e−03	2.9e−05	1.9e−07	7.4	8.0e−06	2.8e−09	1.1e−12	11.4
(1,4)	3.3e−02	2.9e−04	2.0e−06	7.0	1.8e−04	9.2e−08	4.0e−11	11.0
(2,1)	3.1e−04	1.5e−06	7.7e−09	7.6	7.5e−08	2.3e−11	2.3e−14	10.8
(2,2)	1.2e−03	7.0e−06	3.8e−08	7.5	2.4e−07	1.9e−10	5.4e−14	11.0
(2,3)	1.1e−02	5.8e−05	3.0e−07	7.6	1.7e−05	3.7e−09	1.6e−12	11.7
(3,1)	6.0e−03	3.2e−05	1.9e−07	7.5	8.7e−06	2.8e−09	1.1e−12	11.5
(3,2)	1.1e−02	5.8e−05	3.0e−07	7.6	1.7e−05	3.7e−09	1.6e−12	11.7
(4,1)	3.3e−02	2.9e−04	2.0e−06	7.0	1.8e−04	9.2e−08	4.0e−11	11.0

表 6 　　　　　　　　Lax−Friedrichs 　　　　10
Tab.6　Convergence for the first 10 eigenvalues of operator with Lax−Friedrichs flux and locally divergence−free basis

	$N=3$				$N=5$			
	h	$h/2$	$h/4$		h	$h/2$	$h/4$	
(1,1)	3.6e−06	1.6e−08	6.3e−11	7.9	1.0e−10	3.5e−14	3.8e−13	4.0
(1,2)	3.6e−04	1.6e−06	6.7e−09	7.9	1.1e−07	3.2e−11	1.8e−12	8.0
(1,3)	5.7e−03	4.6e−05	2.1e−07	7.3	1.0e−05	5.3e−09	4.9e−12	10.5
(1,4)	6.9e−02	5.1e−04	2.6e−06	7.3	5.3e−04	2.0e−07	3.1e−12	13.7
(2,1)	3.6e−04	1.6e−06	6.7e−09	7.9	1.1e−07	3.3e−11	1.4e−12	8.1
(2,2)	1.3e−03	6.6e−06	2.6e−08	7.8	6.1e−07	1.6e−10	7.7e−13	9.8
(2,3)	1.1e−02	7.0e−05	3.1e−07	7.6	2.0e−05	6.8e−09	3.7e−11	9.5
(3,1)	1.1e−02	4.6e−05	2.1e−07	7.8	2.1e−05	5.4e−09	1.8e−13	13.4
(3,2)	1.1e−02	7.0e−05	3.1e−07	7.6	2.0e−05	6.8e−09	6.5e−12	10.8
(4,1)	6.9e−02	5.1e−04	2.6e−06	7.3	5.3e−04	2.0e−07	6.8e−11	11.5

　　　　1~ 　6 　　　　　　　　　, 　　　　　　　　　　　　　, 　　　　　　　　　　　　　　,
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The Spectral Method of Eigenvalue Problem of Maxwell's Equation

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Abstract: In the traditional differential equation solution, the multi-region spectral method only constructs the approximation scheme of the equation independently in the local element, and different elements exchange information by penalizing the boundary or the numerical flow function on the boundary, which has good flexibility and high precision in the selection of the basis function and the generation of the grid. In this paper, the numerical solution of Maxwell Differential Equation is studied based on multi-region spectral method. In order to further reduce the computational cost of solving the equation, various difference numerical flux formats are introduced. By use of the upwind flux, the scale of the hybrid model supported by the format is reduced. The non-physical eigenvalues cannot be removed and the spectra are clearly separated, which makes it possible to separate the physical mode from the mixed mode. The algorithm is suitable for arbitrary mesh generation with high precision and high efficiency, and the effectiveness of the algorithm is verified by numerical examples.

Key words: Maxwell Equation; multi-domain Galerkin spectral method; convergence order

Bauschinger Effect of Damping Winding Connector of Hydro-Generator Set

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Abstract: The reduction of strain resistance caused by different compression variables and reverse strain of damping winding coupling material of hydro-generator set is studied, which is called Bauschinger effect, abbreviated as BE. The influence of different compression strain variables on damping winding connector BE was discussed. Through different compression strain compression and tension experiments, the optimal Baussinger extremum of damping winding copper connector was obtained. The results show that large compression variables have an effect on BE. With the increase of pre-deformation, the Bauschinger effect value changes. When the pre-deformation is 3%, the Bauschinger effect value reaches the extreme value. In addition, when the deformation is increased, the Bauschinger effect value ecreases, and 3% is the optimal shape variable, namely, the failure limit value of damping winding.

Key words: damping winding; Bauschinger effect; shape variable; limit value