Numerical Conformal Mapping onto the Unit Disk with Concentric Circular Slits by the Charge Simulation Method

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Numerical Conformal Mapping
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1 Introduction

Conformal mappings are familiar in science and engineering. However exact mapping functions are not known except for some special domains. The numerical conformal mapping has been an attractive subject in numerical analysis [5, 6, 13].

We here present a method of numerical conformal mapping of multiply-connected domains with closed boundary Jordan curves onto the unit disk with concentric circular slits. It is a basic problem of conformal mapping of multiply-connected domains. If the domain is bounded by a single closed Jordan curve, the problem is identified as Riemann's mapping theorem. We reduce the mapping problem to the Dirichlet problem with a pair of conjugate harmonic functions and employ the charge simulation method [7, 8, 10], where the conjugate harmonic functions are approximated by a linear combination of complex logarithmic potentials. We give an explicit form of approximate mapping function which is continuous with the principal value of logarithmic function.

2 Mapping Theorem

Let \( D \) be a multiply-connected domain with the closed boundary Jordan curves \( C_1, C_2, \ldots, C_n \) in the \( z \)-plane. Consider the conformal mappings \( w = f_l(z; z_0) (z_0 \in D; l = 1, 2, \ldots, n) \) of \( D \) onto the unit disk with concentric circular slits in the \( w \)-plane, where \( C_l \) is mapped onto the unit circle. They are uniquely determined by the

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We take $z_0 = 0$ and abbreviate $f_i(z;0)$ as $f_i(z)$.

Figure 1: Conformal mapping $w = f_i(z)$ onto the unit disk with concentric circular slits by the charge simulation method.

**Problem 1** Let $D$ be bounded, and $C_1$ and $C_2, \ldots, C_n$ be the outer and inner boundary curves as shown in Figure 1. Our problem is to construct an approximate mapping function of $w = f_i(z)$, which normalization conditions are $f_i(0) = 0$ and $f_i'(0) > 0$. As a result, $C_1$ and $C_2, \ldots, C_n$ are mapped onto the unit circle and the concentric circular slits $S_2, \ldots, S_n$ with the radii $r_2, \ldots, r_n$.

We express the mapping function as

$$f_i(z) = \frac{z}{r_D} \exp(g(z) + ih(z))$$

where $g(z)$ and $h(z)$ are conjugate harmonic functions in $D$, and $r_D$ is a positive constant. The boundary condition $|f_i(z)| = r_l (z \in C_l)$ requires

$$g(z) + \log |z| - \log r_D = \log r_l \quad (z \in C_l; \ l = 1, 2, \ldots, n),$$

$$r_1 = 1,$$

and the normalization condition $f_i'(0) = 1/r_D$ requires

$$g(0) + ih(0) = 0.$$
Conversely, if (2), (3) and (4) are satisfied, (1) is the mapping function of the problem. From the uniqueness of the solution, the problem is now reduced to finding the conjugate harmonic functions $g(z)$ and $h(z)$ together with the radii $R_1, R_2, \ldots, R_n$ and the constant $R_D$.

The conformal mappings $w = f_l(z)$ $(l = 2, \ldots, n)$ for the same bounded domain $D$ and $w = f_l(z)$ $(l = 1, 2, \ldots, n)$ for the unbounded domain $D'$ exterior to the closed Jordan curves $C_1, C_2, \ldots, C_n$ are reduced to Problem 1 by the pre-mappings

$$z^*(z) = \frac{1}{z - \zeta_{l0}} + \frac{1}{\zeta_{l0}},$$

(5)

where $\zeta_{l0}$ is a point inside $C_l$, $(l = 2, \ldots, n)$ for $D$ and $(l = 1, 2, \ldots, n)$ for $D'$, respectively. The solutions are given by

$$f_l(z) = \exp \left\{ i \arg \left( \frac{1}{\zeta_{l0}^2} \right) \right\} f_l^*(z^*).$$

(6)

We abbreviate $f_1(z)$ as $f(z)$.

### 3 Numerical Method

We approximate $g(z)$ and $h(z)$ by a linear combination of complex logarithmic potentials and have an approximate mapping function

$$F(z) = \frac{z}{R_D} \exp(G(z) + iH(z)), \quad G(z) + iH(z) = Q_0 + \sum_{l=1}^{n} \sum_{i=1}^{N_l} Q_{li} \log(z - \zeta_{li})$$

(7)

(8)

where $N_l$ charge points $\zeta_{l1}, \zeta_{l2}, \ldots, \zeta_{lN_l}$ are placed outside $C_1$ or inside $C_l$ $(l = 2, \ldots, n)$. The complex constant $Q_0$ and the real charges $Q_{li}$ are determined to satisfy the requirement for the outer charges [3],

$$\sum_{i=1}^{N_l} Q_{1i} = -1,$$

(9)

the requirement for $H(z)$ to be single-valued in $D$,

$$\sum_{i=1}^{N_l} Q_{li} = 0 \quad (l = 2, \ldots, n),$$

(10)

and the boundary conditions (2) and (3) at the same number of collocation points $z_{l1}, z_{l2}, \ldots, z_{lN_l}$ on $C_l$ $(l = 1, 2, \ldots, n)$, i.e., the linear equations called collocation condition,

$$G(z_{mj}) - \log R_m - \log R_D = -\log |z_{mj}|$$

$$z_{mj} \in C_m; \ j = 1, 2, \ldots, N_m; \ m = 1, 2, \ldots, n)$$

(11)
If \( C_1, C_2, \ldots, C_n \) are starlike with respect to the origin and \( \zeta_{20}, \ldots, \zeta_{n0} \) inside \( C_2, \ldots, C_n \), using (10), we can rewrite (8) to

\[
G(z) + iH(z) = Q_0 + \sum_{l=1}^{N_1} Q_{1l} \log(z - \zeta_{1l}) + \sum_{l=2}^{n} \sum_{i=1}^{N_l} Q_{li} \log(z - \zeta_{li})
\]

\[
= Q_0 + \sum_{i=1}^{N_1} Q_{1i} \left\{ \log \left( 1 - \frac{z}{\zeta_{1i}} \right) + \log(-\zeta_{1i}) \right\}
\]

\[
+ \sum_{l=2}^{n} \sum_{i=1}^{N_l} Q_{li} \log \left( \frac{z - \zeta_{li}}{z - \zeta_{l0}} \right)
\]

(13)

for \( H(z) \) to be continuous in \( D \) with the principal value of complex logarithmic function. From the normalization condition (4),

\[
G(0) + iH(0) = Q_0 + \sum_{i=1}^{N_1} Q_{1i} \log(-\zeta_{1i}) + \sum_{l=2}^{n} \sum_{i=1}^{N_l} Q_{li} \log \left( \frac{\zeta_{li}}{\zeta_{l0}} \right) = 0.
\]

(14)

We eliminate \( Q_0 \) from (13) and (14), and obtain the following algorithm.

**Algorithm 1** If \( C_1, C_2, \ldots, C_n \) are starlike with respect to the origin and \( \zeta_{20}, \ldots, \zeta_{n0} \) inside \( C_2, \ldots, C_n \), the approximate mapping function is given by

\[
F(z) = \frac{z}{R_D} \exp(G(z) + iH(z)),
\]

\[
G(z) + iH(z) = \sum_{i=1}^{N_1} Q_{1i} \log \left( 1 - \frac{z}{\zeta_{1i}} \right) + \sum_{l=2}^{n} \sum_{i=1}^{N_l} Q_{li} \left\{ \log \left( \frac{z - \zeta_{li}}{z - \zeta_{l0}} \right) - \log \left( \frac{\zeta_{li}}{\zeta_{l0}} \right) \right\}
\]

where the charges \( Q_{11}, Q_{12}, \ldots, Q_{nN_n} \), the radii \( R_1, R_2, \ldots, R_n \) and the constant \( R_D \) are solutions of the \( N_1 + N_2 + \cdots + N_n + n + 1 \) simultaneous linear equations

\[
\sum_{i=1}^{N_1} Q_{1i} \log \left| 1 - \frac{z_{mj}}{\zeta_{1i}} \right| + \sum_{l=2}^{n} \sum_{i=1}^{N_l} Q_{li} \left( \log \left| \frac{z_{mj} - \zeta_{li}}{z_{mj} - \zeta_{l0}} \right| - \log \left| \frac{\zeta_{li}}{\zeta_{l0}} \right| \right)
\]

\[
- \log R_m - \log R_D = -\log |z_{mj}|
\]

\((z_{mj} \in C_m; j = 1, 2, \ldots, N_m; m = 1, 2, \ldots, n)\),

\[
R_1 = 1,
\]

\[
\sum_{i=1}^{N_1} Q_{1i} = -1,
\]

\[
\sum_{i=1}^{N_l} Q_{li} = 0 \ (l = 2, \ldots, n).
\]
The algorithm gives an approximate mapping function in the case of Riemann's mapping theorem \([1, 3]\) if \(n = 1\).

In general cases, using (9) and (10), we should rewrite (8) to

\[
G(z) + iH(z) = Q_0 + \sum_{l=1}^{n} \left\{ Q_{l1} \log(z - \zeta_{l1}) + \sum_{i=2}^{N_l} \left( \sum_{k=1}^{i} Q_{lk} - \sum_{k=1}^{i-1} Q_{lk} \right) \log(z - \zeta_{li}) \right\}
\]

\[
= Q_0 + \sum_{l=1}^{n} \left( \sum_{i=1}^{N_l-1} \left( \sum_{k=1}^{i} Q_{lk} \right) \log(z - \zeta_{li}) \right)
\]

\[
= Q_0 + \sum_{l=1}^{n} \sum_{i=1}^{N_l-1} \left( \sum_{k=1}^{i} Q_{lk} \right) \log \left( \frac{z - \zeta_{li}}{z - \zeta_{li+1}} \right) - \log(z - \zeta_{1N_l})
\]

(15)

for \(H(z)\) to be continuous in \(D\) with the principal value of complex logarithmic function.

From the normalization condition (4),

\[
G(0) + iH(0) = Q_0 + \sum_{l=1}^{n} \sum_{i=1}^{N_l-1} \left( \sum_{k=1}^{i} Q_{lk} \right) \log \left( \frac{\zeta_{li}}{\zeta_{li+1}} \right) - \log(-\zeta_{1N_l}) = 0
\]

(16)

We eliminate \(Q_0\) from (15) and (16), and obtain the following algorithm.

**Algorithm 2** The approximate mapping function is given by

\[
F(z) = \frac{z}{R_D} \exp(G(z) + i(H(z)),
\]

\[
G(z) + iH(z) = \sum_{l=1}^{n} \sum_{i=1}^{N_l-1} Q_l^i \left\{ \log \left( \frac{z - \zeta_{li}}{z - \zeta_{li+1}} \right) - \log \left( \frac{\zeta_{li}}{\zeta_{li+1}} \right) \right\} - \log \left( 1 - \frac{z}{\zeta_{1N_l}} \right)
\]

where the unknown constants, the partial sums of the charges

\[
Q_l^i = \sum_{k=1}^{i} Q_{lk} \quad (i = 1, 2, \ldots, N_l - 1; \ l = 1, 2, \ldots, n),
\]

the radii \(R_1, R_2, \ldots, R_n\) and the constant \(R_D\) are solutions of the \(N_1+N_2+\cdots+N_n+1\) simultaneous linear equations

\[
\sum_{i=1}^{N_l-1} Q_l^i \left\{ \log \left| \frac{z_{mj} - \zeta_{li}}{z_{mj} - \zeta_{li+1}} \right| - \log \left| \frac{\zeta_{li}}{\zeta_{li+1}} \right| \right\}
\]

\[
- \log R_m - \log R_D = - \log |z_{mj}| + \log \left| 1 - \frac{z_{mj}}{\zeta_{1N_l}} \right|
\]

\((z_{mj} \in C_m; \ j = 1, 2, \ldots, N_m; \ m = 1, 2, \ldots, n),
\]

\(R_1 = 1.\)
The charge point $\zeta_{1N_{1}}$ should be placed for the discontinuity of $\text{Arg}(1 - z/\zeta_{1N_{1}})$ not to intersect $D$.

From the maximum modulus theorem for analytic functions, the error takes its maximum value somewhere on $C_{1}, C_{2}, \ldots, C_{n}$ and is estimated as

$$E_{F}(z) = |F(z) - f(z)| \leq \max_{z \in C_{1} \cup C_{2} \cup \ldots \cup C_{n}} |F(z) - f(z)| = E_{F}.$$ (17)

### 4 An Example

We use Algorithm 1 and compute

$$E_{Ml} = \max_{1 \leq j \leq N_{l}} |F(z_{l}j+1/2) - R_{l}|, \quad E_{RL} = |R_{l} - R_{ld}| \quad (l = 1, 2, \ldots, n),$$

$$E_{RD} = |R_{D} - R_{Dd}|$$

for error estimation, where $z_{l}j+1/2$ is the middle point on $C_{l}$ between $z_{lj}$ and $z_{lj+1}$, and $R_{ld}$ and $R_{Dd}$ are obtained by doubling the number of simulation charges.

**Example 1** A triply-connected domain,

$$C_{1} : x^{2}/4^{2} + y^{2} = 1, \quad C_{2} : |z - 1.2| = 0.3, \quad C_{3} : |z + 1| = 0.6,$$

$$\zeta_{20} = 1.2, \quad \zeta_{30} = -1.$$

Collocation points and charge points are

$$z_{1j} = z \left( \frac{5}{3} \mathrm{e}^{i\theta_{j}} \right), \quad \zeta_{1j} = z \left( \sqrt{\frac{5}{3}} \mathrm{e}^{-i\theta_{j}} \right),$$

$$z_{2j} = 0.3 \mathrm{e}^{i\theta_{j}} + 1.2, \quad \zeta_{2j} = 0.3 \mathrm{e}^{i\theta_{j}} + 1.2,$$

$$z_{3j} = 0.6 \mathrm{e}^{i\theta_{j}} - 1, \quad \zeta_{3j} = 0.6 \mathrm{e}^{i\theta_{j}} - 1, \quad \theta_{j} = \frac{2\pi(j - 1)}{N} \quad (j = 1, 2, \ldots, N)$$

using Joukowski’s transformation

$$z(t) = \frac{\sqrt{a^{2} - b^{2}}}{2} \left( t + \frac{1}{t} \right) \quad (a = 4, b = 1),$$

where $0 < q < 1$ is a parameter for charge arrangement.

Figure 2 and Table 1 show the results. The values of $R_{l}$ or $R_{D}$ are shown until a nonzero digit appears in $|R_{l} - R_{ld}|$ or $|R_{D} - R_{Dd}|$, and $\text{cond}$ is the $L_{1}$ condition number of the coefficient matrix to be solved. If $q = 0.8$ for $N = 128$, then the results are $E_{M1} = 9.1 \times 10^{-8},$ $E_{M2} = 4.9 \times 10^{-14},$ $E_{M3} = 6.9 \times 10^{-14}$ and $\text{cond} = 3.0 \times 10^{8}$.

Reichel [11] applied a first kind integral equation method [12] to the same problem and obtained $E_{M1} = 4.3 \times 10^{-3}, R_{1} = 2.50000001,$ $E_{M2} = 5.5 \times 10^{-4}, R_{2} = 1.9555848,$ $E_{M3} = 3.8 \times 10^{-3}, R_{3} = 1.744207$ for, roughly speaking, $N = 63$, where $r_{1} = 2.5$ is the capacity of $C_{1}$. The accuracy of the charge simulation method is an order of magnitude higher though the values of Table 1 should be multiplied by 2.5 for comparison.
Figure 2: Numerical conformal mapping of the domain bounded by an ellipse and two circles ($N = 32, q = 0.5$).

Table 1: Numerical results ($q = 0.5$), where * shows the case of ill-conditioning.

<table>
<thead>
<tr>
<th>$N$</th>
<th>$E_{MI}$</th>
<th>$E_{RI}$</th>
<th>$R_i$</th>
<th>$E_{RD}$</th>
<th>$R_D$</th>
<th>$\text{cond}$</th>
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<td>16</td>
<td>$C_1$</td>
<td>2.7E-02</td>
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<td>1.</td>
<td></td>
<td>5.9E03</td>
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<tr>
<td></td>
<td>$C_2$</td>
<td>7.8E-06</td>
<td>2.8E-03</td>
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<td>7.5E-03</td>
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<td></td>
<td>$C_3$</td>
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<td>0.</td>
<td>1.</td>
<td></td>
<td>3.1E06</td>
</tr>
<tr>
<td></td>
<td>$C_2$</td>
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<td>1.1E-04</td>
<td>0.7821</td>
<td>1.9E-04</td>
<td>0.8980</td>
</tr>
<tr>
<td></td>
<td>$C_3$</td>
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<td>6.4E-04</td>
<td>0.6970</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>1.</td>
<td></td>
<td>4.0E11</td>
</tr>
<tr>
<td></td>
<td>$C_2$</td>
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<td>$C_3$</td>
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<tr>
<td>128</td>
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<td>1.</td>
<td></td>
<td>3.5E19*</td>
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<td>$C_2$</td>
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<td>$C_3$</td>
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</table>
5 Concluding Remarks

We have presented a method of numerical conformal mapping of multiply-connected domains with closed boundary Jordan curves onto the unit disk with concentric circular slits. The advantages of the method are:

- High accuracy by simple computation for domains with curved boundaries.
- An explicit form of approximate mapping function continuous with the principal value of logarithmic function.

Conventional methods of numerical conformal mapping do not necessarily give an approximate mapping function which is continuous in the problem domain though case-by-case correction is possible.

See Amano [2], and Amano and Sugihara [4] for the numerical conformal mapping of unbounded multiply-connected domains onto parallel, circular and radial slit domains.

References


