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<tr>
<td>Citation</td>
<td>数理解析研究所講究録 (1996), 944: 68-76</td>
</tr>
<tr>
<td>Issue Date</td>
<td>1996-04</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/2433/60199">http://hdl.handle.net/2433/60199</a></td>
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<tr>
<td>Type</td>
<td>Departmental Bulletin Paper</td>
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<td>Textversion</td>
<td>publisher</td>
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Numerical Calculation of Scattering State by Means of Higher Order Radiation Boundary Condition

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KAKO, Takashi (加古孝, 電気通信大学 情報工学科 * )

1 Introduction

The stationary scattering state of an acoustic wave with a time frequency $k$ scattered by some bounded obstacle $\Omega$ in the Euclidean space $\mathbb{R}^n$ satisfies the following Helmholtz equation with the Sommerfeld radiation condition at infinity:

\[
\begin{align*}
\tag{H}
-\Delta u - k^2 u &= 0 & \text{in } \Omega^c \equiv \mathbb{R}^n / \Omega, & \Delta = \sum_{i=1}^n \partial^2 / \partial x_i^2, \\
 u(x) &= -\varphi_0(x) & \text{on } \partial \Omega, \\
 \sqrt{r} (\frac{\partial u}{\partial r} - ik u) &\to 0, & r = |x| \to \infty.
\end{align*}
\]

Here $\Omega$ is a bounded obstacle with smooth boundary $\partial \Omega$ and $\varphi_0(x)$ is the boundary value of some incident wave.

In this paper, we study the case where the space dimension $n$ is two. In section 2, modifying the Sommerfeld radiation condition, we find some higher order radiation condition. We construct in section 3 a sequence of approximate solutions to the scattering state for which the higher order radiation boundary condition is imposed on an artificial boundary. Our radiation condition is non-local and contains only bounded operators in its expression. Hence it is rather easy to calculate numerically. Applying the finite element method to these auxiliary problems in section 4, we propose an algorithm to calculate approximate numerical solutions to (H). We give error estimates for respective approximations and show some numerical examples in section 5.

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2 Higher order radiation condition

Assume that $\Omega$ has a non-empty interior and includes the origin: $0 \in \Omega$. Choosing a number $R_0$ with the property: $\Omega \subset \mathbb{B}_{R_0} \equiv \{x ||x| \leq R_0\}$ and a smooth function $\chi_{R_0}(x)$ such that

\[
\chi_{R_0}(x) = \begin{cases} 
1 & (|x| \leq R_0) \\
0 & (|x| \geq R_0 + 1),
\end{cases}
\]

we define a function $v(x) \equiv (1 - \chi_{R_0}(x))u(x)$. From (H), the function $v$ satisfies the equation:

\[
(H_t) \quad \left\{ \begin{array}{l}
-\Delta v - k^2 v = f, \quad \text{supp } f \subset B_{R_1} \backslash B_{R_0}, \\
\sqrt{r} \left( \frac{\partial v}{\partial r} - ikv \right) \rightarrow 0, \quad r = |x| \rightarrow \infty,
\end{array} \right.
\]

where $f = (-\Delta - k^2)(1 - \chi_{R_0}(x))u(x)$. When $n = 2$, the zeroth order Hankel function of the first kind, $H_0^{(1)}(kr)$, satisfies the equation:

\[
-\Delta \left( \frac{i}{4} H_{0}^{(1)}(k|x-x'|) \right) - k^2 \left( \frac{i}{4} H_{0}^{(1)}(k|x-x'|) \right) = \delta(x-x'),
\]

\[
\sqrt{r} \left( \frac{\partial}{\partial r} \frac{i}{4} H_{0}^{(1)}(k|x-x'|) - ik H_{0}^{(1)}(k|x-x'|) \right) \rightarrow 0, \quad r = |x| \rightarrow \infty.
\]

This means that the function $\frac{i}{4} H_{0}^{(1)}(k|x-x'|)$, $x' \in B_{R_0+1}$, is Green’s function of $(H_t)$. Noticing that

\[
H_0^{(1)}(k|x-x'|) \simeq \frac{1}{\sqrt{r}} e^{i\theta} \sum_{p=0}^{\infty} ikr \frac{d_p(\tilde{x}, x')}{r^p}, \quad r \rightarrow \infty,
\]

for fixed $x'$ with $\tilde{x} \equiv \frac{x}{|x|} = e^{i\theta}$, we have the asymptotic expansion of $v(x)$ as $r$ tends to infinity: $v(x) \simeq \frac{1}{\sqrt{r}} e^{i\theta} \sum_{p=0}^{\infty} a_p(\theta) \frac{d_p(\tilde{x}, x')}{r^p}$, where $a_p(\theta) = \int_{B_{R_0+1}} \frac{i}{4} d_p(\tilde{x}, x') f(x') dx'$. We define $w(x) \equiv \sum_{p=0}^{\infty} a_p(\theta) r^p$ and $\rho(r; \lambda) \equiv \sqrt{r} e^{-ikr}$, then $w(x) = \rho(r; \lambda) v(x)$. Multiplying $\rho(r; \lambda)$ to (2), we get $-\rho \Delta (\frac{i}{4} e^{i\theta} w) - \lambda w = \rho f$. Finally the relation (2) is rewritten as

\[
\left\{ \begin{array}{l}
-\Delta w + \left( -\frac{1}{4r^2} + \frac{1}{r} - 2ik \frac{\partial}{\partial r} \right) w = \rho f; \\
\frac{\partial w}{\partial r} \rightarrow 0, \quad r = |x| \rightarrow \infty.
\end{array} \right.
\]

In particular, when $r$ is sufficiently large, we have $\rho f = 0$. From the definition of $w$, we have the asymptotic relation:

\[
\sum_{p=0}^{N} \{- p(p+1) a_p(\theta) + 2ikp a_p(\theta) + \frac{1}{4r^2} a_p(\theta) - \frac{1}{r^2} \Delta a_p(\theta) \} = O(r^{-N-2}).
\]

This leads to the recursion formula:

\[
a_p(\theta) = \frac{1}{2ikp} \{ \Lambda_\theta + p(p-1) - \frac{1}{4} \} a_{p-1}(\theta), \quad p = 1, 2, 3, \ldots,
\]

where $\Lambda_\theta = -\frac{1}{4r^2} + \frac{1}{r} - 2ik \frac{\partial}{\partial r}$.

In particular, when $r$ is sufficiently large, we have $\rho f = 0$. From the definition of $w$, we have the asymptotic relation:

\[
\sum_{p=0}^{N} \{- p(p+1) a_p(\theta) + 2ikp a_p(\theta) + \frac{1}{4r^2} a_p(\theta) - \frac{1}{r^2} \Delta a_p(\theta) \} = O(r^{-N-2}).
\]
with $\Lambda_\theta \equiv \frac{\partial^2}{\partial \theta^2}$. We put $B(0) \equiv 1$ and define the operators $L(p)$ and $B(p)$, $p = 1, 2, \ldots$, as $L(p) \equiv \frac{1}{2 \pi i p} \{ \Lambda_\theta + p(p-1) - \frac{1}{4} \}$ and $B(p) \equiv L(p)L(p-1)\ldots L(1)$. Then we have the following expression: $a_p(\theta) = B(p)a_0(\theta)$, $p = 0, 1, 2, \ldots$. Accordingly, the solution $u(r, \theta)$ of (H) has an asymptotic expansion as $r$ tends to infinity:

$$u(r, \theta) \simeq \frac{1}{\sqrt{r}} e^{ik r} \left( \sum_{p=0}^{N} \frac{B(p)}{r^p} \right) a_0(\theta) + O(r^{-N-1-1/2}),$$  (7)

and we have the asymptotic expansions for $\partial u/\partial r$:

$$\frac{\partial u}{\partial r} \simeq i k u - \frac{1}{2r} u + \frac{1}{\sqrt{r}} e^{ik r} \left( \sum_{p=1}^{N} \frac{-p}{r^{p+1}} B(p) \right) a_0(\theta) + O(r^{-N-2-1/2}).$$  (8)

In particular, we have, for $N = 1$,

$$\frac{\partial u}{\partial r} - i k u + \frac{1}{2r} u + \frac{1}{\sqrt{r}} e^{ik r} B(1) a_0(\theta) = O(r^{-7/2})$$  (9)

and

$$u(r, \theta) = \frac{1}{\sqrt{r}} e^{ik r} (1 + \frac{1}{r} B(1)) a_0(\theta) + O(r^{-5/2}).$$  (10)

Obviously, we have the estimate:

$$||(1 + \frac{1}{r} B(1))^{-1}||_{L^2(S^1) \rightarrow H^2(S^1)} < \infty.$$  (11)

Hence, from (10) we have the following asymptotic relation in $L^2(S^1)$:

$$||a_0 - \sqrt{r} e^{-ik r} (1 + \frac{1}{r} B(1))^{-1} u||_{H^2(S^1)} = O(r^{-2}).$$  (12)

Putting (12) into (9), we get the estimate:

$$||\left( \frac{\partial}{\partial r} - ik + \frac{1}{2r} \right) u + \frac{1}{r^2} B(1) (1 + \frac{1}{r} B(1))^{-1} u||_{L^2(S^1)} = O(r^{-7/2}).$$  (13)

We define an operator $T_r$ as $T_r \equiv \frac{1}{r} B(1) (1 + \frac{1}{r} B(1))^{-1}$. Then we have the following lemma and theorem:

**Lemma 2.1** The operator $T_r$ is bounded in $L^2(S^1)$ with norm $||T_r||_{L^2(S^1)} \leq 1$.

**Theorem 2.2** There exists one and only one solution of the Helmholtz equation (H) which satisfies the followings:

$$\left\{ \begin{array}{ll}
-\Delta u(x) - k^2 u(x) &= 0 \quad \text{in } \Omega^c, \\
u(x) &= -\varphi_0 \quad \text{on } \partial\Omega, \\
\end{array} \right.$$  (14)
3 Analytical approximation problem

We put $R \gg 1$, and let $u_R$ be the solution of the boundary value problem:

\[ \begin{align*}
&\Delta u_R - k^2 u_R = 0 \quad \text{in } \Omega^c_R \equiv \Omega^c \cap B_R, \\
&\varphi_0 + u_R|_{\partial \Omega} = 0, \\
&D_* u_R = 0 \quad \text{on } \partial B_R.
\end{align*} \tag{15} \]

Here $D_* \equiv \partial/\partial r - ik + 1/(2R) + (1/R)T_R$. Using the same function $\rho(r; \lambda) = \sqrt{r}e^{-ikr}$ as in section 2, we put, for $R_0 < R$, $v_R(x) \equiv \rho(r; \lambda)(u_R(x) + \chi_{R_0}(x)\varphi_0(x))$. Then $v_R(x)$ satisfies the following equation

\[ \begin{align*}
&\Delta v_R + \left( -\frac{1}{4r^2} + \left( \frac{1}{r} - 2ik \right) \frac{\partial}{\partial r} \right) v_R = g \quad \text{in } \Omega^c_R, \\
&v_R|_{\partial \Omega} = 0, \\
&(\frac{\partial v_R}{\partial r} + \frac{1}{R}T_Rv_R)|_{S_R} = 0.
\end{align*} \tag{16} \]

with $g = -\Delta(\rho(r; \lambda)\chi_{R_0}(x)\varphi_0(x)) + (-1/4r^2 + (1/r - 2ik)\partial/\partial r)(\rho(r; \lambda)\chi_{R_0}(x)\varphi_0(x))$. Since the operator $T_R$ is bounded, we can define bounded operator $e^{(r/R)T_R}$, $r \in \mathbb{R}$.

We introduce two operators $H_R$ and $Q_R$ as follows: $\mathcal{D}(H_R) \equiv \{u| u \in H^2(\Omega^c_R), u|_{\partial \Omega} = 0 \}$ and $\mathcal{D}(Q_R) = \mathcal{D}(H_R)$, $Q_Ru = -2T_R\frac{\partial u}{\partial r} - T^2_Ru - 2ikT_Ru - 2ik\frac{\partial u}{\partial r} - \frac{1}{4r^2}u + \frac{1}{r}\frac{\partial u}{\partial r} - u$. Then the equation (17) becomes an operator theoretical equation:

\[ \begin{align*}
(H_R + 1)w_R + Q_Rw_R = f_R.
\end{align*} \tag{18} \]

Putting $w_R \equiv (H_R + 1)\varpi_R$, we have the equation in $L^2(\Omega^c_R)$ for $w_R$:

\[ \begin{align*}
w_R + Q_R(H_R + 1)^{-1}w_R = f_R.
\end{align*} \tag{19} \]

**Theorem 3.1** The equation (18) has a unique solution in $L^2(\Omega^c_R)$ given by

\[ \begin{align*}
\varpi_R = (H_R + 1)^{-1}(1 + Q_R(H_R + 1)^{-1})^{-1}f_R.
\end{align*} \tag{20} \]

**Proof.** By Rellich's compactness theorem, the operator $Q_R$ is relatively compact with respect to $H_R + 1$ and hence $Q_R(H_R + 1)^{-1}$ is compact. In order to prove the existence of the solution of the equation (19), we use the Fredholm alternative theorem. Hence we have
only to show that the solution $w_{R}$ of equation (19) is zero when the right hand of (19) $f_{R}$ is zero. Let $w_{R}$ is a solution of (19) with $f_{R} = 0$. Put $u_{R} = r^{-\frac{1}{2}}e^{i\kappa r}\{e^{-(r/R)T_{R}}(H_{R} + 1)^{-1}w_{R}\}$. Then from (19), we have (15) and

$$\int_{\Omega_{R}}((\Delta u_{R})\overline{u_{R}} - u_{R}\Delta u_{R})\,dx = 0.$$  \hspace{1cm} (21)

Using Green's formula, we obtain

$$\int_{S_{R}}(\overline{u_{R}}\frac{\partial u_{R}}{\partial r} - u_{R}\frac{\partial u_{R}}{\partial r})\,ds_{R} = 0,$$  \hspace{1cm} (22)

and, from the boundary condition $D_{\lambda}u_{R} = 0$,

$$0 = \int_{S_{R}}\{2ik|u_{R}|^{2} + \frac{1}{R}(u_{R}\overline{T_{R}u_{R}} - (T_{R}u_{R})\overline{u_{R}})\}\,dS_{R}.$$  

Hence, using Lemma 2.1, we have

$$\|u_{R}\|^{2}_{L^{2}(S_{R})} = \int_{S_{R}}|u_{R}|^{2}\,dS_{R} = \frac{1}{2ikR}\int_{S_{R}}\{(T_{R}u_{R})u_{R} - (T_{R}u_{R})\overline{u_{R}}\}\,dS_{R} \leq \frac{1}{kR}\|u_{R}\|^{2}_{L^{2}(S_{R})}.$$  

Then $u_{R} \equiv 0$ on $S_{R}$ when $kR > 1$, and we also have $\frac{\partial u_{R}}{\partial r} = (ik - \frac{1}{2R} - \frac{1}{R}T_{R})u_{R} = 0$ in $S_{R}$. Finally from the unique continuation property, we have $u_{R} \equiv 0$ in $\Omega_{R}$. This proves the uniqueness and hence the existence of the solution of the equation (19).

Next, we estimate the difference between $u$ and $u_{R}$. Putting $e_{R} \equiv u - u_{R}$, we have the equation for $e_{R}(x)$:

$$\begin{cases}
-\Delta e_{R} - k^{2}e_{R} = 0 & \text{in } \Omega_{R}^{c}, \\
D_{\lambda}e_{R} = D_{\lambda}u & \text{on } S_{R}.
\end{cases}$$  \hspace{1cm} (23)

In the same manner as in the proof of Theorem 3.1, we obtain

$$0 = \int_{S_{R}}\{(D_{\lambda}e_{R})\overline{e_{R}} - e_{R}D_{\lambda}\overline{e_{R}}\}\,dS_{R} - 2ik\int_{S_{R}}|e_{R}|^{2}\,dS_{R} - \frac{1}{R}\int_{S_{R}}((T_{R}e_{R})\overline{e_{R}} - (T_{R}e_{R})\overline{e_{R}})\,dS_{R}.$$  

Hence we have the estimate:

$$\|e_{R}\|^{2}_{L^{2}(S_{R})} = \int_{S_{R}}|e_{R}|^{2}\,dS_{R} \leq \frac{1}{2kR}\int_{S_{R}}\{(T_{R}e_{R})\overline{e_{R}} - (T_{R}e_{R})\overline{e_{R}}\}\,dS_{R} + \frac{1}{2kR}\int_{S_{R}}\{(D_{\lambda}e_{R})\overline{e_{R}} - e_{R}D_{\lambda}\overline{e_{R}}\}\,dS_{R} \leq \frac{1}{kR}\|T_{R}e_{R}\|_{L^{2}(S_{R})}\|e_{R}\|_{L^{2}(S_{R})} + \frac{1}{kR}\|D_{\lambda}u\|_{L^{2}(S_{R})}\|e_{R}\|_{L^{2}(S_{R})} \leq \frac{1}{kR}\|e_{R}\|^{2}_{L^{2}(S_{R})} + \frac{1}{kR}\|D_{\lambda}u\|_{L^{2}(S_{R})}\|e_{R}\|_{L^{2}(S_{R})}.$$
Combining the estimate for $||D_{\lambda}u||_{L^{2}(S_{R})}$ in (K), in section 2, we have

$$||e_{R}||_{L^{2}(S_{R})} \leq \frac{1}{(1-\frac{1}{kR})k}||D_{\lambda}u_{R}||_{L^{2}(S_{R})} \leq O(R^{-7/2}).$$

**Theorem 3.2** When $R \gg 1$, with some constant $C$, the estimates

$$\int_{S_{R}}|e_{R}|^{2}dS_{R} \leq CR^{-7} \tag{24}$$

and, for a fixed $R_{0}$,

$$\sup_{x \in \Omega^{c}_{R}}|e_{R}(x)| \leq CR^{-3} \tag{25}$$

hold.

\section{4 Discrete approximation}

For large enough $R$, we consider the weak formulation of the boundary value problem $(K_{R})$:

$$a_{R}(u, v) + b_{R}(u, v) = (g, v), \text{ for all } v \in V_{R}. \tag{26}$$

Here, $a_{R}(u, v) = \int_{\Omega_{R}^{c}} \left( \frac{\partial u}{\partial r} \frac{\partial \overline{v}}{\partial r} + \frac{1}{r^{2}} \frac{\partial u}{\partial \theta} \frac{\partial \overline{v}}{\partial \theta} + u \overline{v} \right) r dr d\theta$, and $b_{R}(u, v) = b_{R}^{1}(u, v) + b_{R}^{2}(u, v)$, with $b_{R}^{1}(u, v) \equiv \int_{\Omega_{R}^{c}} \left( \left( \frac{1}{r} - 2ik \right) \frac{\partial}{\partial r} - 1 - \frac{1}{4r^{2}} \right) u \overline{v} r dr d\theta$, $b_{R}^{2}(u, v) \equiv \int_{S_{R}} \frac{1}{R} T_{R} u \overline{v} dS_{R}$, and $u \in V_{R} \equiv H_{D}^{1}(\Omega_{R}^{c}) = \{ u \mid u \in H^{1}(\Omega_{R}^{c}), u|_{\partial \Omega} = 0 \}$. We consider the finite element method for this equation in the same way as in [4]. But we have to treat the term $b_{R}^{2}$ appropriately. For this purpose we approximate $b_{R}^{2}(u, v)$ in the following way. Consider the problem:

$$\left( 1 + \frac{1}{2ikR} \left( \frac{\partial^{2}}{\partial \theta^{2}} - \frac{1}{4} \right) \right) w_{i}(\theta) = \varphi_{i}(\theta, R) \tag{27}$$

$$w_{i}(0) = w_{i}(2\pi), \quad \frac{dw_{i}}{d\theta}|_{\theta = 0} = \frac{dw_{i}}{d\theta}|_{\theta = 2\pi}. \tag{28}$$

The weak formulation of the above equation is to find $w^{i}$ such that

$$\int_{0}^{2\pi} \left( \frac{i}{2kR} \frac{\partial w^{i}}{\partial \theta} \overline{v} \theta + (1 + \frac{i}{8kR})w^{i} \overline{v} \right) - \varphi_{i}(\theta, R) \overline{v} d\theta = 0, \tag{29}$$

for all $v \in H_{D}^{1}(S_{R})$. 

Here, $H_1^1(S_R) = \{ v \mid v \in H^1(S_R), v(0) = v(2\pi), \frac{dv}{d\theta}|_{\theta=0} = \frac{dv}{d\theta}|_{\theta=2\pi} \}$. The approximation of $w_i(\theta)$ is calculated by the following set of linear equations:

$$
\sum_{\ell=1}^{n(h)} \zeta_{\ell} \int_0^{2\pi} \left( \frac{i}{2kR} \frac{\partial \psi_k(\theta)}{\partial \theta} \frac{\partial \psi_{\ell}(\theta)}{\partial \theta} + (1 + \frac{i}{8kR}) \psi_k(\theta) \overline{\psi_{\ell}(\theta)} - \varphi_i(\theta, R) \overline{\psi_{\ell}(\theta)} \right) d\theta = 0 \quad (30)
$$

for all $\psi_k(\theta) \in \mathcal{W}_h \subset H_1^1(S_R), \ k=1,2,\ldots, n(h)$.

Here $\mathcal{W}_h$ is a $n(h)$-dimensional subspace of $H_1^1(S_R)$, whose basis functions are piecewise linear on $S_R$.

5 Numerical results

We set an another boundary value problem (cf [4]):

$$
(G_R) \left\{ \begin{array}{l}
-\Delta u_R - k^2 u_R = 0 \quad \text{in} \quad \Omega_R^c \equiv \Omega^c \cap B_R, \\
\varphi_0 + u_R = 0 \quad \text{on} \quad \partial \Omega, \\
D_{\lambda} \equiv \frac{\partial u}{\partial r} - ik u_R + \frac{1}{2R} u_R = 0 \quad \text{on} \quad S_R = \partial B_R.
\end{array} \right. \quad (31)
$$

We express the boundary condition in (31) as $A_1$, and the one in $(K_R)$ as $A_2$. The weak formulation of $(G_R)$ is the same as (26) with $b_R(v, v) \equiv 0$. We have made two algorithms by FEM to calculate the solutions of the two boundary value problems and compare the two numerical results calculated by these algorithms. We consider 2D star-shaped obstacles. Then its boundary can be expressed by a function $f(\theta)$ of $\theta$: $\partial \Omega = \{(x, y) | x = f(\theta) \sin(\theta), y = f(\theta) \cos(\theta), 0 \leq \theta \leq 2\pi\}$.

**Example 1** When $f(\theta) = 1$ and $\varphi_0(r, \theta) = H_{n}^{(1)}(kr) \cos(n\theta)$, we put $u_R^{i}, i = 1,2$ to be the solutions of the boundary value problem with boundary condition $A_i$, and $u_{R,h}^{i}, i = 1,2$ to be the numerical solutions with boundary condition $A_i$. Suppose the following order relations:

$$
||u_R^{i} - u_{R,h}^{i}||_{L^2(B_R)} \simeq C_0 \gamma_i h^\gamma_i, \quad (32)
$$

and

$$
\beta_i(h) = ||u_{R,h}^{i} - u_{R,h}^{i+1}||_{L^2(B_R)} \simeq C_i \gamma_i h^\gamma_i, \quad (33)
$$

then we have

$$
\gamma_i = \frac{\log(\beta_i(2h)) - \log(\beta_i(h))}{\log(2)}, \quad (34)
$$

We get numerically the order $2\gamma$ as follows:
Putting $\Delta = \{(r, \theta) | 1 \leq r \leq 2\}$ and $u$ be the solution of (H), $u_{R}^{i}$ the solutions of $(K'_{R})$ and $(G_{R}) i = 1, 2$, and $u_{R,h}^{i}$ the solutions of the weak formulation of $(K_{R})$ and $(G_{R})$. we get the estimate:

\[
||u - u_{R,h}^{i}||_{L^2(\Delta)} = ||u - u_{R}^{i} + u_{R}^{i} - u_{R,h}^{i}||_{L^2(\Delta)} \\
\leq ||u - u_{R}^{i}||_{L^2(\Delta)} + ||u_{R}^{i} - u_{R,h}^{i}||_{L^2(\Delta)} \\
\leq \sup_{x \in \Delta} |u - u_{R}^{i}|(m(\Delta))^\frac{1}{2} + C_{2}(u_{R}^{i})h^{2} \\
\leq C_{1}R^{-i+1} + C_{2}(u_{R}^{i})h^{2}.
\]

(35)

We try to confirm it by numerical calculation. The following table shows $\epsilon_{R}^{i} = ||u - u_{R,h}^{i}||_{L^2(\Delta)}$ when $k = 5, n = 1$ and $\varphi_{0} = H_{1}^{(1)}(5r) \cos(\theta)$.

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<th>3.</th>
<th>4.</th>
<th>5.</th>
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Table 3  Error $\epsilon_{R}^{i}$

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<td>0.92</td>
<td>0.903</td>
</tr>
<tr>
<td>16</td>
<td>0.20</td>
<td>0.17</td>
<td>0.17</td>
<td>0.098</td>
<td>0.053</td>
<td>0.0703</td>
<td>0.0609</td>
<td>0.0647</td>
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<tr>
<td>32</td>
<td>0.106</td>
<td>0.098</td>
<td>0.094</td>
<td>0.0248</td>
<td>0.0038</td>
<td>0.00435</td>
<td>0.00395</td>
<td>0.0044</td>
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<tr>
<td>64</td>
<td>0.086</td>
<td>0.109</td>
<td>0.0695</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
From the estimate (35), we get, when $R \to \infty$,

$$||u - u_{R,h}^i||_{L^2(\Delta)} \to C_2(u_{R,h}^i)h^2.$$  

(36)

The numerical results are consistent with this assumption with $C_2(u_{R,h}^i) \sim C$:

$$||u - u_{R,h}^i||_{L^2(\Delta)} \simeq Ch^\gamma, \quad R > 10.$$  

(37)

<table>
<thead>
<tr>
<th>$2\gamma \setminus R$</th>
<th>40</th>
<th>30</th>
<th>20</th>
<th>10</th>
</tr>
</thead>
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<tr>
<td>$A_1$</td>
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<td>3.9444391</td>
<td>4.00957997</td>
<td>3.49959478</td>
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<tr>
<td>$A_2$</td>
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<td>3.9456009</td>
<td>4.013786059</td>
<td>3.6851072</td>
</tr>
</tbody>
</table>

**Table 4** Convergence order $2\gamma$

**References**


