Creating materials with a desired refraction coefficient: numerical experiments

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Abstract
A recipe for creating materials with a desired refraction coefficient is implemented numerically. The following assumptions are used:

\[ \zeta_m = h(x_m)/a^\kappa, \quad d = O(a^{(2-\kappa)/3}), \quad M = O(1/a^{2-\kappa}), \quad \kappa \in (0, 1), \]

where \( \zeta_m \) and \( x_m \) are the boundary impedance and center of the \( m \)-th ball, respectively, \( h(x) \in C(D) \), \( \Im h(x) \leq 0 \), \( M \) is the number of small balls embedded in the cube \( D \), \( a \) is the radius of the small balls and \( d \) is the distance between the neighboring balls.

An error estimate is given for the approximate solution of the many-body scattering problem in the case of small scatterers. This result is used for the estimate of the mimimal number of small particles to be embedded in a given domain \( D \) in order to get a material whose refraction coefficient approximates the desired one with the relative error not exceeding a desired small quantity.

MSC: 65R20, 65Z05, 74Q10
Key words: many-body wave scattering problem, metamaterials, refraction coefficient

1 Introduction
A theory of wave scattering by many small bodies embedded in a bounded domain \( D \) filled with a material with known refraction coefficient was developed in [1]-[4]. It was assumed in [1] that

\[ d = O(a^{1/3}), \quad M = O(a^{-1}), \quad \frac{\partial u_M}{\partial \nu} = \zeta_m u_M \text{ on } S_m, \quad 1 \leq m \leq M, \]

where \( a \) is the characteristic size of the small particles, \( d \) is the distance between two neighboring particles, \( M \) is the total number of the embedded particles, \( S_m \)
is the boundary of $m$-th particle $D_m$, $\nu$ is the unit normal to $S_m$ directed out of $D_m$, and $\zeta_m = h_m/a$, where $h_m$, $\text{Im} h_m \leq 0$, $1 \leq m \leq M$, are constants independent of $a$.

Let us assume that $D$ is filled with a material with known refraction coefficient $n_0^2(x)$, $\text{Im} n_0^2(x) \geq 0$, $n_0^2(x) = 1$ in $D' := \mathbb{R}^2 \setminus D$, $n_0^2(x)$ is Riemann integrable. The governing equation is
\[ L_0 u_0 := [\triangle + k^2 n_0^2] u_0 = 0, \quad \text{in } \mathbb{R}^3, \] (1)
\[ u_0 = \exp(ik x \cdot \alpha) + v_0 \] (2)
where $k$ is the wave number, $\alpha \in S^2$ is the direction of the incident plane wave, $S^2$ is the unit sphere in $\mathbb{R}^3$, and $v_0$ is the scattered field satisfying the radiation condition
\[ \lim_{r \to \infty} r \left( \frac{\partial v_0}{\partial r} - ik v_0 \right) = 0, \quad r := |x| \to \infty, \] (3)
and the limit is attained uniformly with respect to the directions $x^0 := x/r$.

Let $n^2(x)$ be a desired refraction coefficient in $D$. We assume that $n^2(x)$ is Riemann integrable, $\text{Im} n^2(x) \geq 0$, $n^2(x) = 1$ in $D'$. Our objective is to create materials with the refraction coefficient $n^2(x)$ in $D$ by embedding into $D$ many small non-intersecting balls $B_m$, $1 \leq m \leq M$, of radius $a$, centered at some points $x_m \in D$. If one embeds $M$ small particles $B_m$ in the bounded domain $D$, then the scattering problem consists of finding the solution to the following problem:
\[ L_0 u_M := [\triangle + k^2 n_0^2] u_M(x) = 0, \quad x \in \mathbb{R}^3 \setminus \bigcup_{m=1}^M B_m, \] (4)
\[ \frac{\partial u_M}{\partial \nu} = \zeta_m u_M \quad \text{on } S_m := \partial B_m, \quad 1 \leq m \leq M, \] (5)
\[ u_M = u_0 + v_M, \] (6)
where $u_0$ solves problem (1)-(3), and $v_M$ satisfies the radiation condition.

The following theorem is proved in [4] under the assumptions
\[ \zeta_m = h(x_m)/a^\kappa, \quad d = O(a^{2-\kappa}/3), \quad M = O(1/a^{2-\kappa}), \quad \kappa \in (0, 1), \] (7)
where $h(x)$ is a continuous function in $D$, $\text{Im} h \leq 0$, and $\kappa \in (0, 1)$ is a parameter one can choose as one wishes. Below it is always assumed that conditions (7) hold.

**Theorem 1.1** ([4]). Assume that conditions (7) are satisfied, and $D_m$ is a ball of radius $a$ centered at a point $x_m$. Let $h(x)$ in (7) be an arbitrary continuous function in $D$, $\text{Im} h(x) \leq 0$, $\Delta_p \subset D$ be any subdomain of $D$, and $N(\Delta_p)$ be the number of particles in $\Delta_p$,
\[ N(\Delta_p) = \frac{1}{a^{2-\kappa}} \int_{\Delta_p} N(x) dx [1 + o(1)], \quad a \to 0, \] (8)
where $N(x) \geq 0$ is a given continuous function in $D$. Then

$$\lim_{a \to 0} \|u_e(x) - u(x)\|_{C(D)} = 0,$$

where

$$u_e(x) := u_0(x) - 4\pi \sum_{j=1}^{M} G(x, x_j) h(x_j) u_e(x_j) a^{2-\kappa}[1 + o(1)], \quad a \to 0, \quad (10)$$

where $\min_j |x - x_j| \geq a$, and $G(x, y)$ is the Green function of the operator $L_0$ in $\mathbb{R}^3$, $G(x, y)$ satisfies the radiation condition. The numbers $u_e(x_j), 1 \leq j \leq M,$ are found from the linear algebraic system:

$$u_e(x_m) = u_0(x_m) - 4\pi \sum_{j=1, j\neq m}^{M} G(x_m, x_j) h(x_j) u_e(x_j) a^{2-\kappa}, \quad m = 1, 2, \ldots, M,$$

which is uniquely solvable for all sufficiently large $M$. The function $u(x) = \lim_{a \to 0} u_e(x)$ solves the following limiting equation:

$$u(x) = u_0(x) - \int_{D} G(x, y) p(y) u(y) dy,$$

where $u_0$ satisfies equations (1)-(3),

$$p(x) := 4\pi N(x) h(x), \quad (13)$$

$$n^2(x) := 1 - k^{-2} q(x), \quad (14)$$

$$q(x) := q_0(x) + p(x), \quad q_0(x) := k^2 - k^2 n_0^2(x), \quad (15)$$

and $n_0^2(x)$ is the coefficient in (1).

In [4] a recipe for creating material with a desired refraction coefficient is formulated.

The goal of this paper is to implement numerically the recipe for creating materials with a desired refraction coefficient in a given domain $D$ by embedding in $D$ many small particles with prescribed physical properties. These particles are balls of radius $a$, centered at the points $x_m \in D$, and their physical properties are described by the boundary impedances $\zeta_m = h(x_m)/a^\kappa$. A formula for embedding the small balls in $D$ is given in Section 2.

We give an estimate for the error in the refraction coefficient of the medium obtained by embedding finitely many ($M < \infty$) small particles, compared with the refraction coefficient of the limiting medium ($M \to \infty$). This is important because in practice one cannot go to the limit $M \to \infty$, i.e., $a \to 0$, and one has to know the maximal $a$ (i.e., minimal $M$) such that the corresponding to
this a refraction coefficient differs from the desired refraction coefficient by not more than a given small quantity. In Section 3 we give an algorithm for finding the minimal number \( M \) of the embedded small balls which generate a material whose refraction coefficient differs from a desired one by not more than a desired small quantity. In Section 4 some numerical experiments are described.

2 Embedding small balls into a cube

In this section we give a formula for distributing small balls in a cube in such a way that the second and third restrictions (17) are satisfied.

Without loss of generality let us assume that the domain \( D \) is the unit cube:

\[
D := [0, 1] \times [0, 1] \times [0, 1].
\]  

(16)

Let

\[
D = \bigcup_{q=1}^{n^3} \Delta_q, \quad n \in \mathbb{N}, \quad \Delta_i \cap \Delta_j = \emptyset \quad \text{for} \quad i \neq j,
\]  

(17)

where \( \mathbb{N} \) is the set of positive integers, \( \overline{X} \) is the closure of the set \( X \), and \( \Delta_q, q = 1, 2, \ldots, n^3 \), are cubes of side length \( 1/n \).

**Definition:** We say that \( D \) has property \( Q_n \) if each small cube \( \Delta_q \) contains a ball of radius \( a_n, 0 < a_n < 1/n \), centered at the centroid of the cube \( \Delta_q \), and the following condition holds

\[
d_n := \min_{q \neq j} \text{dist}(B_{a_n}(x_q), B_{a_n}(x_j)) = \gamma a_n^{(2-\kappa)/3},
\]

(18)

where \( x_q \) is the centroid of the cube \( \Delta_q \), \( q = 1, 2, \ldots, n^3 \),

\[
B_a(x) := \{ y \in \mathbb{R}^3 \mid |y - x| < a \},
\]

(19)

and \( \gamma > 0 \) is a constant which is not too small (see formula (25)).

From (17) and (18) one gets

\[
d_n = l_n - 2a_n = \gamma a_n^{(2-\kappa)/3}, \quad l_n := 1/n.
\]

(20)

Since \( l_n = 1/n \), the quantity \( a_n \) solves the equation

\[
\gamma a_n^{(2-\kappa)/3} + 2a - 1/n = 0.
\]

(21)

The function \( f(a) := \gamma a^{(2-\kappa)/3} + 2a \) is strictly growing on \([0, \infty)\). Thus, the solution to equation (21) exists, is unique, and can be calculated numerically, for example, by the bisection method.

However, it is easy to derive an analytic asymptotic formula for \( a_n \) as \( n \to \infty \). This formula is simple and can be used for all \( n \) we are interested in, since these \( n \) are sufficiently large.

Let us derive this asymptotic formula. Since \( 1/3 < (2-\kappa)/3 < 2/3 \), one has \( a \ll a^{(2-\kappa)/3} \) if \( a \ll 1 \). Therefore,

\[
a_n = \left[1/(n\gamma)\right]^{3/(2-\kappa)}[1 + o(1)], \quad \text{as} \quad n \to \infty,
\]

(22)
is the desired asymptotic formula for the solution to (21). Note that
\[
\lim_{n \to \infty} a_n = 0 \quad \text{and} \quad \lim_{n \to \infty} na_n = 0, \tag{23}
\]
as follows from (22) because \(3/(2 - \kappa) > 1\).

We note that \(a_n/d_n \ll 1\), if \(n \gg 1\), because (20) yields
\[
a_n/d_n = a_n/(\gamma a_n^{(2 - \kappa)/3}) = a_n^{(1+\kappa)/3} \gamma^{-1} \ll 1. \tag{24}
\]

Let us choose \(n\) sufficiently large so that
\[
\gamma \gg (l_n/2)^{(1+\kappa)/3}, \quad \kappa \in (0, 1), \quad l_n = 1/n, \tag{25}
\]
and make the following assumption:

Assumption A): \(D\) has property \(Q_{mP}\). Here \(D = \bigcup_{q=1}^{P^3} \Omega_q\), \(\Omega_j \cap \Omega_i = \emptyset\) for \(j \neq i\), where each cube \(\Omega_q\) has side length \(1/P\), and \(m^3\) small balls are embedded in \(\Omega_q\) so that the following two conditions hold:

1. Each cube \(\Omega_q\) is a union of small sub-cubes \(\Delta_{j,q}\):
   \[
   \Omega_q = \bigcup_{j=1}^{m^3} \Delta_{j,q}, \quad \Delta_{i,q} \cap \Delta_{j,q} = \emptyset \quad \text{for} \quad i \neq j, \tag{26}
   \]
   where \(\Delta_{j,q}\), \(j = 1, 2, \ldots, m^3\), \(q = 1, 2, \ldots, P^3\), are cubes of side length \(1/(mP)\),

2. In each sub-cube \(\Delta_{j,q}\) there is a ball of radius \(a_{mP}\), \(0 < a_{mP} < 1/(mP)\), centered at the centroid of the sub-cube \(\Delta_{j,q}\), and the radius \(a_{mP}\) of the embedded balls satisfies the relation
   \[
   1/(mP) - 2a_{mP} = \gamma a_{mP}^{(2 - \kappa)/3}, \quad \gamma \gg [1/(2mP)]^{(\kappa+1)/3}, \tag{27}
   \]
where \(\gamma > 0\) is a fixed constant.

**Lemma 2.1.** If Assumption A) holds, then
\[
\lim_{m \to \infty} Ma_{mP}^{2 - \kappa} = 1/\gamma^3, \tag{28}
\]
where \(M = (mP)^3\) is the total number of small balls embedded in the unit cube \(D\), \(\gamma > 0\) is fixed, and
\[
a_{mP} = [1/(\gamma mP)]^{3/(2 - \kappa)}[1 + o(1)] \quad \text{as} \quad m \to \infty. \tag{29}
\]

**Proof.** Relation (29) is an immediate consequence of (27). Using this relation, one obtains
\[
\lim_{m \to \infty} Ma_{mP}^{2 - \kappa} = \lim_{m \to \infty} (mP)^3 a_{mP}^{2 - \kappa}
\]
\[
= \lim_{m \to \infty} (mP)^3 [1/(\gamma mP)]^{3}[1 + o(1)]
\]
\[
= \lim_{m \to \infty} (1/\gamma^3)[1 + o(1)] = 1/\gamma^3. \tag{30}
\]

Lemma 2.1 is proved. \[\square\]
3 A recipe for creating materials with a desired refraction coefficient

In this section the recipe given in [4] is used for creating materials with a desired refraction coefficient by embedding into $D$ small balls so that Assumption A) holds.

**Step 1.** Given the refraction coefficient $n_0^2(x)$ of the original material in $D$ and the desired refraction coefficient $n^2(x)$ in $D$, one calculates

$$p(x) = k^2[n_0^2(x) - n^2(x)] = p_1(x) + ip_2(x), \quad (31)$$

where

$p_1 := \text{Re } p(x)$ and $p_2(x) := \text{Im } p(x)$.

Choose

$$N(x) = 1/\gamma^3, \quad (32)$$

where $\gamma$ is the constant $\gamma$ in Assumption A).

**Step 2.** Choose

$$h(x) = h_1(x) + ih_2(x), \quad (33)$$

where the functions $h_1(x)$ and $h_2(x)$ are defined by the formulas:

$$h_i(x) = \gamma^3 p_i(x)/(4\pi), \quad i = 1, 2, \quad (34)$$

and the functions $p_i(x)$ are defined in **Step 1**.

**Step 3.** Partition $D$ into $P$ small cubes $\Omega_p$ with side length $1/P$, and embed $m^3$ small balls in each cube $\Omega_p$ so that Assumption A) holds.

Then

$$N(\Omega_p) = \frac{1}{a_{mP}^{2-\kappa}} \int_{\Omega_p} N(x)dx = |\Omega_p|/(\gamma^3 a_{mP}^{2-\kappa}) = 1/[(\gamma P a_{mP}^{(2-\kappa)/3})^3], \quad (35)$$

where $N(\Delta_p)$ is the number of the balls embedded in the cube $\Omega_p$, $\kappa \in (0, 1)$, $a_{mP}$ is the radius of the embedded balls, and $|\Omega_p|$ is the volume of the cube $\Omega_p$. Since

$$a_{mP} = [1/(m\gamma P)]^{2\kappa/(1+\kappa)} [1+o(1)] \quad as \quad m \to \infty,$$

it follows that

$$\lim_{m \to \infty} \frac{N(\Omega_p)}{m^3} = 1. \quad (36)$$

By Assumption A) the balls are situated at the distances $\gamma a_{mP}^{2-\kappa} \gamma > [1/(mP)]^{1+\kappa}$. Therefore, all the assumptions, made in Theorem 1.1 hold. Thus,

$$\max_{x \in D} |u_\epsilon(x) - u(x)| \to 0 \quad as \quad M \to \infty, \quad (37)$$
where $u_\epsilon(x)$ is defined in (10) and $u(x)$ solves (12). Let us assume for simplicity that $n_0^2(x) = 1$, so that

$$G(x, y) = g(x, y) := \exp(ik|x - y|)/(4\pi|x - y|).$$

Then

$$u_\epsilon(x) = u_0(x) - 4\pi \sum_{j=1}^{M} g(x, x_j)h(x_j)u_\epsilon(x_j)a^2_{mP}, \quad |x - x_j| > a_{mP}, \quad M := (mP)^3,$$

and the limiting function

$$u(x) = \lim_{M \to \infty} u_\epsilon(x)$$

solves the integral equation

$$u(x) + Tu(x) = u_0(x), \quad (39)$$

where

$$Tu(x) := \int_D g(x, y)p(y)u(y)dy, \quad (40)$$

$$g(x, y) := \exp(ik|x - y|)/(4\pi|x - y|), \quad (41)$$

$$M := (mP)^3, \quad h(x) = h_1(x) + ih_2(x), \quad h_i(x), i = 1, 2,$$ are defined in (44),

$$p(x) = k^2[n_0^2(x) - n^2(x)] = 4\pi[h_1(x) + ih_2(x)]N(x) = 4\pi[h_1(x) + ih_2(x)]/\gamma^3, \quad (42)$$

and the function $u_0(x)$ in (38) solves the scattering problem (1)-(3).

It follows from (37) that

$$\max_{1 \leq l \leq M} |u(x_l) - u_\epsilon(x_l)| \to 0 \text{ as } M \to \infty, \quad (43)$$

where $u_\epsilon(x)$ and $u(x)$ are defined in (38) and (39), respectively. Here and throughout this paper $D := \cup_{j=1}^{M} D_j$, $M := (mP)^3$, $D_j$ ($j = 1, 2, \ldots, M$) are cubes with the side length $1/(mP)$, $D_j \cap D_l = \emptyset$ for $j \neq l$, and $x_j$ denotes the center of the cube $D_j$. However, since (37) was not proved here, let us prove relation (43). We denote

$$\|u\|_\infty := \sup_{x \in D} |u(x)| \quad \text{and} \quad \|v\|_{CM} := \max_{1 \leq j \leq M} |v_j|, \quad v := \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_M \end{pmatrix} \in \mathbb{C}^M,$$
where \( \mathbb{C} \) is the set of complex numbers.

Consider the following piecewise-constant function as an approximate solution to equation (39):

\[
  u_{(M)}(x) := \sum_{j=1}^{M} \chi_j(x) u_{j,M},
\]

(44)

where \( u_{j,M} (j = 1, 2, \ldots, M) \) are constants and

\[
  \chi_j(x) := \begin{cases} 
    1, & x \in D_j, \\
    0, & \text{otherwise}.
  \end{cases}
\]

(45)

Substituting \( u_{(M)}(x) \) for \( u(x) \) in (39) and evaluating at points \( x_l \), one gets the following linear algebraic system (LAS) which is used to find the unknown \( u_{j,M} \):

\[
  \tilde{u}_{(M)} + T_{d,M} \tilde{u}_{(M)} = u_{0,M},
\]

(46)

where \( T_{d,M} \) is a discrete version of \( T_M \), defined below,

\[
  \tilde{u}_{(M)} := \begin{pmatrix} u_{1,M} \\ u_{2,M} \\ \vdots \\ u_{M,M} \end{pmatrix} \in \mathbb{C}^M, \quad u_{0,M} := \begin{pmatrix} u_0(x_1) \\ u_0(x_2) \\ \vdots \\ u_0(x_M) \end{pmatrix} \in \mathbb{C}^M,
\]

(47)

\( u_0(x) \) solves problem (1)-(3), and

\[
  (T_{d,M}v)_l := \sum_{j=1}^{M} \int_{D_j} g(x_l, y)p(y)dyv_j, \quad l = 1, 2, \ldots, M, \quad v := \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_M \end{pmatrix} \in \mathbb{C}^M.
\]

(48)

Multiplying the \( l \)-th equation of (46) by \( \chi_l(x), \ l = 1, 2, \ldots, M \), and summing up over \( l \) from 1 to \( M \), one gets

\[
  u_{(M)}(x) = u_{0,(M)}(x) - T_M u_{(M)}(x),
\]

(49)

where \( u_{(M)}(x) \) is defined in (44),

\[
  u_{0,(M)}(x) := \sum_{j=1}^{M} \chi_j(x) u_0(x_j),
\]

(50)

and

\[
  T_M u(x) := \sum_{j=1}^{M} \chi_j(x) \int_D g(x_j, y)p(y)u(y)dy, \quad M = (mP)^3.
\]

(51)

It was proved in \([5]\) that equation (49) is equivalent to (46) in the sense that \( \{u_{j,M}\}_{j=1}^{M} \) solves (46) if and only if function (44) solves (49).
Lemma 3.1. For all sufficiently large $M$ equation (46) has a unique solution, and there exists a constant $c_1 > 0$ such that

$$
\|(I_{d,M} + T_{d,M})^{-1}\| \leq c_1, \quad \forall M > M_0,
$$

(52)

where $M_0 > 0$ is a sufficiently large number.

Proof. Consider the operators $T$ and $T_M$ as operators in the space $L^\infty(D)$ with the sup-norm. Let $\|(T - T_M)u\|_\infty := \sup_{x \in D} |(T - T_M)u(x)|$. Then

$$
\|(T - T_M)u\|_\infty \leq \max_i \sup_{x \in D} \sum_{j=1}^M \int_{D_j} |(g(x,y) - g(x_i,y))p(y)u(y)| \, dy
$$

$$
\leq \|u\|_\infty \|p\|_\infty \max_i \sup_{x \in D} \sum_{j=1}^M \int_{|x-x_j| \leq \frac{1}{M} \|D\|} |g(x,y) - g(x_i,y)| \, dy
$$

$$
\leq O(1/(mP)).
$$

(53)

This implies

$$
\|T - T_M\| = O(1/(mP)) = O(1/M^{1/3}) \to 0 \text{ as } M \to \infty.
$$

(54)

The operator $I + T$ is known to be boundedly invertible, so $\|(I + T)^{-1}\| < c$, where $c > 0$ is a constant. Therefore,

$$
I + T_M = (I + T)[I + (I + T)^{-1}(T_M - T)].
$$

(55)

By (54) there exists $M_0$ such that

$$
\|(I + T)^{-1}(T_M - T)\| \leq c\|T_M - T\| < \delta < 1, \quad \forall M > M_0,
$$

(56)

where $\delta > 0$ is a constant. From (56) we obtain, $\forall M > M_0,$

$$
\|[I + (I + T)^{-1}(T_M - T)]^{-1}\| \leq \frac{1}{1 - \|[(I + T)^{-1}(T_M - T)]^{-1}\|} \leq 1/(1 - \delta).
$$

(57)

Therefore, it follows from (55) that $I + T_M$ is boundedly invertible and

$$
(I + T_M)^{-1} = [I + (I + T)^{-1}(T_M - T)]^{-1}(I + T)^{-1},
$$

(58)

so there exists a constant $c_0 > 0$ such that

$$
\|(I + T_M)^{-1}\| \leq c_0, \quad \forall M > M_0.
$$

(59)

Since (49) is equivalent to (46), it follows that the homogeneous equation $v + T_{d,M}v = 0$ has only trivial solution for $M > M_0$, i.e., $\mathcal{N}(I_{d,M} + T_{d,M}) = \{0\}$ for $M > M_0$, where $\mathcal{N}(A)$ is the nullspace of the operator $A$, $I_{d,M}$ is the identity operator in $C^M$ and $T_{d,M}$ is defined in (48). Therefore, by the Fredholm alternative equation (46) is solvable for $M > M_0$. This together with (59) yield the existence of a constant $c_1 > 0$ such that $\|(I_{d,M} + T_{d,M})^{-1}\| \leq c_1$ for $M > M_0$. Lemma 3.1 is proved. □
Define $T_d : C^2(D) \to \mathbb{C}^M$ as follows

$$(T_d w)_l := (T w)(x_l) = \sum_{j=1}^{M} \int_{D_j} g(x_l, y)p(y)w(y)dy, \quad l = 1, 2, \ldots, M,$$

and

$$u_M := \begin{pmatrix} u(x_1) \\ u(x_2) \\ \vdots \\ u(x_M) \end{pmatrix} \in \mathbb{C}^M,$$

where $T$ is defined in (40) and $u(x)$ solves (39). Then it follows from (39), (60) and (61) that the following equation holds

$$u_M + T_d u = u_{0,M},$$

where $u_{0,M}$ is defined in (47). Using equations (46) and (62), we derive the following equality:

$$(I_{d,M} + T_{d,M})(\tilde{u}_M - u_M) = (I_{d,M} + T_{d,M})u_{\tilde{u}_M} - (I_{d,M} + T_{d,M})u_M = u_{0,M} - (I_{d,M}u_M + T_{d,M}u_M) = u_{0,M} - u_M - T_{d,M}u_M = T_d u - T_{d,M}u_M,$$

where $\tilde{u}_M$ and $u_{0,M}$ are defined in (47).

$$I_{d,M}v = v, \quad \forall v = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_M \end{pmatrix} \in \mathbb{C}^M.$$  

Using relation (63), one gets

$$\tilde{u}_M - u_M = (I_{d,M} + T_{d,M})^{-1}(T_d u - T_{d,M}u_M).$$

**Lemma 3.2.** Let Assumption A) hold (see Section 2 below (24)). Suppose $u(x)$ solves (39) where $p(x) \in C^1$. Then

$$\|\tilde{u}_M - u_M\|_{\mathbb{C}^M} = O(1/M^{2/3}) \text{ as } M \to \infty,$$

where $u_M$ and $\tilde{u}_M$ are defined in (61) and (47), respectively.

**Proof.** By (65) and estimate (52) we obtain

$$\|\tilde{u}_M - u_M\|_{\mathbb{C}^M} \leq \|(I_{d,M} + T_{d,M})^{-1}\|_2 \|T_d u - T_{d,M}u_M\|_{\mathbb{C}^M} \leq c_1\|T_d u - T_{d,M}u_M\|_{\mathbb{C}^M},$$

where $c_1$ is a constant.
where $T_{d,M}$ and $T_d$ are defined in (18) and (19), respectively. Using the identity $u(y) = u(x_j) = u(y) - u(x_j) - Du(x_j)(y - x_j)$ and applying the triangle inequality, we get the estimate

$$
\|T_d u - T_{d,M}u_M\|_{C_M} = \max_{1 \leq l \leq M} \left| \sum_{j=1}^{M} \int_{D_j} g(x_l, y)p(y)(u(y) - u(x_j))dy \right|
$$

$$
\leq \max_{1 \leq l \leq M} \left| \int_{D_l} g(x_l, y)p(y)(u(y) - u(x_l))dy \right|
$$

$$
+ \max_{1 \leq l \leq M} \left| \sum_{j=1, j \neq l}^{M} \int_{D_j} g(x_l, y)p(y)(u(y) - u(x_j))dy \right|
$$

$$
\leq 2\|p\|_{\infty} \max_{1 \leq l \leq M} \left| \int_{D_l} g(x_l, y)p(y)(u(y) - u(x_l))dy \right|
$$

$$
= 2\|p\|_{\infty} \max_{1 \leq l \leq M} \left| \int_{D_l} g(x_l, y)p(y)(u(y) - u(x_l))dy \right|
$$

$$
\leq 2\|p\|_{\infty} \max_{1 \leq l \leq M} \left| \int_{D_l} g(x_l, y)p(y)(u(y) - u(x_l))dy \right|
$$

$$
= 2\|p\|_{\infty} \max_{1 \leq l \leq M} \left| \int_{D_l} g(x_l, y)p(y)(u(y) - u(x_l))dy \right|
$$

where

$$
I_1 := \max_{1 \leq l \leq M} \left| \sum_{j=1, j \neq l}^{M} \int_{D_j} g(x_l, y)p(y)(u(y) - u(x_j) - Du(x_j)(y - x_j))dy \right|
$$

and

$$
I_2 := \max_{1 \leq l \leq M} \left| \sum_{j=1, j \neq l}^{M} \int_{D_j} g(x_l, y)p(y)Du(x_j)(y - x_j)dy \right|
$$

Let us derive an estimate for $I_1$. Using the Taylor expansion, we get

$$
I_1 \leq \|p\|_{\infty} \max_{1 \leq l \leq M} \sum_{j=1, j \neq l}^{M} \left| \int_{D_j} g(x_l, y)p(y)\sup_{0 \leq s \leq 1} |D^2 u(sy + (1-s)x_j)||y-x_j|^2dy \right|
$$
Since \( p \in C^1(D), \ u \in C^2(D), \int_D |g(x,y)|dy < \infty \) and \( |y-x| \leq \frac{\sqrt{7}}{2mP} \) for \( y \in D_j \), it follows from (71) that

\[
I_1 = O\left(1/(mP)^2\right) = O(1/M^{2/3}), \quad \text{as} \quad M \to \infty.
\] (72)

Estimate of \( I_2 \) is obtained as follows. Since \( x_j \) is the center of the cube \( D_j \), it follows that

\[
\int_{D_j} g(x_1, x_j)p(x_j)Du(x_j)(y-x_j)dy = 0, \quad j = 1, 2, \ldots, M.
\] (73)

Therefore, using (73), \( I_2 \) can be rewritten as follows:

\[
I_2 = \max_{1 \leq i \leq M} \left| \sum_{j=1, j \neq i}^M \int_{D_j} (g(x_1, y)p(y) - g(x_1, x_j)p(x_j))Du(x_j)(y-x_j)dy \right|. \quad (74)
\]

Let

\[
g_i(y) := g(x_1, y), \quad (g_i p)(y) = g_i(x_1)p(y), \quad i = 1, 2, \ldots, M.
\] (75)

Then the formulas

\[
| (g_i p)(y) - (g_i p)(x_j) | = \left| \int_0^1 \frac{\partial}{\partial t} g_i(y)(ty + (1 - t)x_j)dt \right|
\]

\[
\leq \sup_{0 \leq t \leq 1} |D_y (g_i p)(ty + (1 - t)x_j)||y-x_j|
\] (76)

and \( D_y (g_i p)(y) = p(y)D_y g_i(y) + g_i(y)Dp(y) \), yield the following estimate:

\[
I_2 \leq \frac{\sqrt{3} \|Du\|_{\infty}}{2mP} \max_{1 \leq i \leq M} \|p\|_{\infty} \int_{D_j} \sup_{0 \leq t \leq 1} |D_y g_i(ty + (1 - t)x_j)||y-x_j|dy
\]

\[
+ \frac{\sqrt{3} \|Du\|_{\infty}}{2mP} \max_{1 \leq i \leq M} \|Dp\|_{\infty} \int_{D_j} \sup_{0 \leq t \leq 1} |g_i(ty + (1 - t)x_j)||y-x_j|dy
\]

\[
\leq c(k) \frac{\|Du\|_{\infty}}{(mP)^2} \max_{1 \leq i \leq M} \|p\|_{\infty} \int_{D_j} \left( \frac{1}{4\pi|x_i-y|^2} + \frac{1}{4\pi|x_i-y|^2} \right)dy
\]

\[
+ \hat{c} \|Du\|_{\infty} \max_{1 \leq i \leq M} \|Dp\|_{\infty} \int_{D_j} \frac{1}{4\pi|x_i-y|}dy = O(1/(mP)^2) = O(1/M^{2/3}),
\] (77)

where \( \hat{c} > 0 \) is a constant and \( c(k) \) is a constant depending on the wave number \( k \). Here the estimates \( |y-x_j| \leq \sqrt{3}/(2mP) \) for \( y \in D_j \), \( \int_{D_j} \frac{1}{4\pi|x_i-y|^2}dy < \infty \) for \( \beta < 3 \), and \( |x_i - y| \leq 2|x_i - s| \) for \( y \in D_j, \ j \neq l, \ s = tx_j + (1 - t)y, \ t \in [0, 1] \), were used. The relation (70) follows from (67), (68), (72) and (74).

Lemma [3.2] is proved. \( \Box \)
Lemma 3.3. Let the Assumption A) hold. Consider the linear algebraic system for the unknowns \( u_e(x_l) \):

\[
u_e(x_l) = u_0(x_l) - 4\pi \sum_{j=1, j \neq l}^M g(x_l, x_j) h(x_j) a_{mP}^{2-\kappa} u_e(x_j), \quad l = 1, 2, \ldots, M,
\]

where \( p(x) = 4\pi h(x) N(x) \in C^2(D) \), \( N(x) = 1/\gamma^3 \), \( M = (mP)^3 \), and \( g(x, y) \) is defined in (90). Then

\[
\| \tilde{u}(M) - u_e,M \|_{C^M} = O \left( \frac{\log M}{M^{2/3}} + |1 - \gamma^3 M a_{mP}^{2-\kappa}| \right) \quad \text{as} \quad M \to \infty,
\]

where \( \tilde{u}(M) \) is defined in (17),

\[
u_e,M := \begin{pmatrix} u_e(x_1) \\ u_e(x_2) \\ \vdots \\ u_e(x_M) \end{pmatrix} \in \mathbb{C}^M,
\]

and \( u_e(x_j), j = 1, 2, \ldots, M \), solve system (78).

Proof. Let us rewrite (78) as

\[
u_e(x_l) = u_0(x_l) - \sum_{j=1, j \neq l}^M g(x_l, x_j) p(x_j) \frac{a_{mP}^{2-\kappa}}{N(x_j)|D_j|} u_e(x_j)|D_j|
\]

\[
= u_0(x_l) - (T_e u_e,M)_l, \quad l = 1, 2, \ldots, M,
\]

where \( p(x) = 4\pi h(x) N(x) \), \( |D_j| = 1/(mP)^3 \) is the volume of the cube \( D_j \), \( N(x) = 1/\gamma^3 \) and

\[
(T_e v)_l := \sum_{j=1, j \neq l}^M g(x_l, x_j) p(x_j) \left( \gamma mP a_{mP}^{(2-\kappa)/3} \right)^3 |D_j| v_j, \quad v = \begin{pmatrix} v_1 \\ v_2 \\ \vdots \\ v_M \end{pmatrix} \in \mathbb{C}^M,
\]

\[
l = 1, 2, \ldots, M.
\]

Let us derive an estimate for \( \| \tilde{u}(M) - u_e,M \|_{C^M} \). Using equations (100) and (81), we obtain

\[
(I_d,M + T_d,M)(\tilde{u}(M) - u_e,M) = (I_d,M + T_d,M)\tilde{u}(M) - (I_d,M + T_d,M)u_e,M
\]

\[
= u_0,M - u_e,M - T_d,M u_e,M = T_e u_e,M - T_d,M u_e,M.
\]
where \( \tilde{u}(M) \) and \( u_{0,M} \) are defined in (47), \( u_{c,M} \), \( T_{d,M} \) and \( T_{e} \) are defined in (80), (48) and (82), respectively. Relation (83) implies

\[
\| \tilde{u}(M) - u_{c,M} \|_{C^M} \leq \| (I_{d,M} + T_{d,M}^{-1}) ||T_{e}u_{c,M} - T_{d,M}u_{c,M} \|_{C^M,}
\]

(84)

where estimate (82) was used.

Let us derive an estimate for \( \| T_{c}u_{c,M} - T_{d,M}u_{c,M} \|_{C^M} \). Using definitions (48) and (82), and applying the triangle inequality, one gets

\[
\| (T_{c} - T_{d,M})u_{c,M} \|_{C^M} = \max_{1 \leq l \leq M} \left| \sum_{j=1, j \neq l}^{M} g_l(x_j)p_{a_{m,p}}(x_j)u_{c}(x_j)D_j \right| - \sum_{j=1}^{M} \int_{D_j} g_l(y)p(y)du_c(x_j)
\]

\[
= \max_{1 \leq l \leq M} \left| \sum_{j=1, j \neq l}^{M} \int_{D_j} (g_l(x_j)p_{a_{m,p}}(x_j) - g_l(y)p(y))du_c(x_j) - \int_{D_l} g_l(y)p(y)du_c(x_l) \right|
\]

\[
\leq \max_{1 \leq l \leq M} \left| \int_{D_l} g_l(y)p(y)du_c(x_l) \right| + \max_{1 \leq l \leq M} \left| \sum_{j=1, j \neq l}^{M} \int_{D_j} g_l(y)p(y)du_c(x_j) \right|
\]

(85)

where \( g_l(y) := g(x_l, y) \), \( p_{a_{m,p}}(x) := p(x) \left( \gamma_m Pe_m^{(2-\kappa)/3} \right)^3 \),

\[
J_0(l) := \int_{D_l} |g(x_l, y)p(y)u_c(x_l)| dy,
\]

\[
J_1(l) := \sum_{j=1, j \neq l}^{M} \left| \int_{D_j} g(x_l, y)(p(y) - p(x_j))u_c(x_j)dy \right|,
\]

\[
J_2(l) := \sum_{j=1, j \neq l}^{M} \left| \int_{D_j} g(x_l, y)(p(x_j) - p_{a_{m,p}}(x_j))u_c(x_j)dy \right|,
\]

and

\[
J_3(l) := \sum_{j=1, j \neq l}^{M} \left| p_{a_{m,p}}(x_j) \int_{D_j} (g(x_l, y) - g(x_l, x_j))u_c(x_j)dy \right|.
\]
Using the estimate \(|x_l - y| \leq \sqrt{3}/(2mP)\) for \(y \in D_t\), one gets the following estimate of \(J_0(l)\):

\[
J_0(l) \leq \|p\|_\infty \|u_\varepsilon\|_{C^M} \int_{D_l} |g(x_l, y)|dy
\]
\[
\leq \left( \int_{B_a(\varepsilon/2mP)} 1 \over 4\pi |x_l - y| dy \right) \|p\|_\infty \|u_\varepsilon\|_{C^M}
\]
\[
= \left( \int_0^{\sqrt{3}/(2mP)} rdr \right) \|p\|_\infty \|u_\varepsilon\|_{C^M}
\]
\[
= {3 \|p\|_\infty \|u_\varepsilon\|_{C^M} \over 2(2mP)^2} = O(1/M^{2/3}),
\]

(90)

where \(B_a(x)\) is defined in (19).

Let us estimate \(J_1(l)\). Using the identity

\[
p(y) - p(x_j) = p(y) - p(x_j) - \nabla p(x_j) \cdot (y - x_j) + \nabla p(x_j) \cdot (y - x_j)
\]

(91)

in (87) and applying the triangle inequality, one obtains

\[
J_1(l) \leq J_{1,1} + J_{1,2},
\]

(92)

where

\[
J_{1,1} := \sum_{j=1,j \neq l}^M \left| \int_{D_j} g(x_l, y)|p(y) - p(x_j) - \nabla p(x_j) \cdot (y - x_j)|u_\varepsilon(x_j) dy \right|
\]

(93)

and

\[
J_{1,2} := \sum_{j=1,j \neq l}^M \left| \int_{D_j} g(x_l, y)\nabla p(x_j) \cdot (y - x_j)u_\varepsilon(x_j) dy \right|
\]

(94)

To get an estimate for \(J_{1,1}\), we apply the Taylor expansion of \(p(x)\) and get

\[
J_{1,1} \leq \frac{\|u_\varepsilon\|_{C^M}}{2} \sum_{j=1,j \neq l}^M \int_{D_j} |g(x_l, y)| \sup_{0 \leq t \leq 1} |\nabla^2 p(ty + (1 - t)x_j)| |y - x_j|^2 dy
\]
\[
\leq \frac{3\|\nabla^2 p\|_\infty \|u_\varepsilon\|_{C^M}}{8(mP)^2} \sum_{j=1,j \neq l}^M \int_{D_j} |g(x_l, y)|dy
\]
\[
= O(1/(mP)^2) = O(1/M^{2/3}) \text{ as } M \to \infty,
\]

(95)

where \(B_a(x)\) is defined in (19), and the estimate \(|y - x_j| \leq \sqrt{3}/(2mP)\), \(y \in D_j\), was used.

Using the identity

\[
\int_{D_j} g(x_l, x_j)\nabla p(x_j) (y - x_j)u_\varepsilon(x_j) dy = 0, \quad j = 1, 2, \ldots, M,
\]

(96)
one derives the following estimate of $J_{1,2}$:

$$ J_{1,2} = \sum_{j=1,j\neq l}^{M} \left| \int_{D_j} (g(x_1, y) - g(x_1, x_j)) D \phi(x_j) \cdot (y - x_j) u_e(x_j) dy \right| $$

$$ \leq \|u_e\|_{C^M} \sum_{j=1,j\neq l}^{M} \int_{D_j} |g(x_1, y) - g(x_1, x_j)| D \phi(x_j) \cdot (y - x_j) dy $$

$$ \leq \sqrt{3} \|p\|_{\infty} \|u_e\|_{C^M} \sum_{j=1,j\neq l}^{M} \int_{D_j} |g(x_1, y) - g(x_1, x_j)| dy $$

$$ \leq \sqrt{3} \|p\|_{\infty} \|u_e\|_{C^M} \sum_{j=1,j\neq l}^{M} \sup_{0 \leq t \leq 1} |Dg(x_1, ty + (1 - t)x_j)| |y - x_j| dy \quad (97) $$

$$ \leq \frac{c(k)\|p\|_{\infty}\|u_e\|_{C^M}}{(mP)^2} \sum_{j=1,j\neq l}^{M} \sup_{0 \leq t \leq 1} \int_{D_j} \frac{1}{4\pi|x_1 - ty - (1 - t)x_j|^2} dy $$

$$ + \frac{c(k)\|p\|_{\infty}\|u_e\|_{C^M}}{(mP)^2} \sum_{j=1,j\neq l}^{M} \sup_{0 \leq t \leq 1} \int_{D_j} \frac{1}{4\pi|x_1 - ty - (1 - t)x_j|^2} dy $$

$$ \leq \frac{c(k)\|p\|_{\infty}\|u_e\|_{C^M}}{(mP)^2} \int_{B_1(x_1)} \left( \frac{1}{4\pi|x_1 - y|} + \frac{1}{4\pi|x_1 - y|^2} \right) dy $$

$$ = O(1/(mP)^2) = O(1/M^{2/3}) \text{ as } M \to \infty, $$

where $c(k)$ is a constant depending on the wave number $k$ and $B_a(x)$ is defined in (19). Here the estimates $|y - x_j| \leq \sqrt{3}/(2mP)$ for $y \in D_j$, $\int_{D_j} \frac{1}{4\pi|x_1 - y|^2} dy < \infty$ for $\beta < 3$, and $|x_1 - y| \leq 2|x_1 - s|$ for $y \in D_j$, $j \neq l$, $s = tx_j + (1 - t)y$, $t \in [0, 1]$, were used. Applying estimates (95) and (97) to (92), we get

$$ J_1(l) = O(1/M^{2/3}), \text{ as } M \to \infty. \quad (98) $$

Let us derive an estimate for $J_2(l)$. From (88) and the definition $p_{a_{mP}}(x) = p(x)(\gamma m P a^{(2-\kappa)/3})^3$ we get

$$ J_2(l) = \|u_e\|_{C^M} \sum_{j=1,j\neq l}^{M} \int_{D_j} |g(x_1, y)||p(x_j)| |1 - (\gamma m P a^{(2-\kappa)/3})^3| dy $$

$$ \leq \|u_e\|_{C^M} \|p\|_{\infty} |1 - (\gamma m P a^{(2-\kappa)/3})^3| \sum_{j=1,j\neq l}^{M} \int_{D_j} |g(x_1, y)| dy $$

$$ \leq \|u_e\|_{C^M} \|p\|_{\infty} |1 - (\gamma m P a^{(2-\kappa)/3})^3| \int_{B_1(x_1)} \frac{1}{4\pi|x_1 - y|^2} dy $$

$$ = \left( \int_0^{\sqrt{\pi}} r dr \right) \|u_e\|_{C^M} \|p\|_{\infty} |1 - (\gamma m P a^{(2-\kappa)/3})^3| $$

$$ = \frac{3}{2} \|u_e\|_{C^M} \|p\|_{\infty} |1 - \gamma^3 M a_{mP}^{(2-\kappa)}| = O(1 - \gamma^3 M a_{mP}^{(2-\kappa)}), $$

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where \( B_a(x) \) is defined in \([19]\). Using the relation \( \lim_{M \to \infty} \gamma^3 M a^{2-\kappa} = 1 \), one gets \( J_2(l) \to 0 \) as \( M \to \infty \). Estimate of \( J_3(l) \) is derived as follows. Using the identity

\[
\int_{D_j} \mathcal{D} g(x_l, x_j)(y - x_j) u_e(x_j) dy = 0, \quad j = 1, 2, \ldots M,
\]

one gets the following estimate:

\[
J_3(l) = \sum_{j=1, j \neq l}^{M} |p_{m, p}(x_j)| \left| u_e(x_j) \int_{D_j} [g(x_l, y) - g(x_l, x_j) - \mathcal{D} g(x_l, x_j) \cdot (y - x_j)] dy \right|
\]

\[
\leq \frac{\|p\|_{\infty}^3 M a^{2-\kappa} \gamma^3}{2} \sum_{j=1, j \neq l}^{M} \sup_{0 \leq t \leq 1} |\mathcal{D}^2 g(x_l, ty + (1-t)x_j)||y - x_j|^2 dy
\]

\[
\leq \frac{3c_M}{8(mP)^2} \sum_{j=1, j \neq l}^{M} \int_{D_j} \sup_{0 \leq t \leq 1} |\mathcal{D}^2 g(x_l, ty + (1-t)x_j)| dy
\]

\[
\leq \frac{c(k) c_M}{(mP)^2} \sum_{j=1, j \neq l}^{M} \int_{D_j} \sup_{0 \leq t \leq 1} \frac{1}{4\pi|x_l - ty - (1-t)x_j|^2} dy
\]

\[
+ \frac{c(k) c_M}{(mP)^2} \sum_{j=1, j \neq l}^{M} \int_{D_j} \sup_{0 \leq t \leq 1} \frac{1}{4\pi|x_l - ty - (1-t)x_j|^3} dy
\]

\[
\leq \frac{c(k) c_M}{(mP)^2} \int_{1/(2mP) < |x_l - y| < \sqrt{3}} \left( \frac{1}{4\pi|x_l - y|} + \frac{1}{4\pi|x_l - y|^2} + \frac{1}{4\pi|x_l - y|^3} \right) dy
\]

\[
\leq \frac{c(k) c_M}{(mP)^2} \int_{1/(2mP)}^{\sqrt{3}} \left( r + 1 + \frac{1}{r} \right) dr
\]

\[
\leq \frac{2c(k) c_M}{(mP)^2} \left[ 1 + \log(\sqrt{3}) - \log \left( 1/(2mP) \right) \right]
\]

\[
= \frac{2c(k) c_M}{M^{2/3}} \left[ 1 + \log(\sqrt{3}) - \log \left( 1/(2M^{1/3}) \right) \right] = O \left( \frac{\log M}{M^{2/3}} \right),
\]

(101)

where \( c_M := \|p\|_{\infty}^3 \gamma^3 M a^{2-\kappa} \), \( c(k) \) is a constant depending on the wave number \( k \). Here the estimates \( |y - x_l| \leq \sqrt{3}/(2mP) \) for \( y \in D_j \), and \( |x_l - y| \leq 2|x_l - s| \) for \( y \in D_j, j \neq l, s = tx_j + (1-t)y, t \in [0, 1] \), were used. Using estimates \([95], [97], [99] \) and \([101]\), one gets relation \([79]\).

Lemma 3.3 is proved. \( \square \)

The following theorem is a consequence of Lemma 3.2 and Lemma 3.3.
Theorem 3.4. Suppose that the assumptions of Lemma 3.2 and Lemma 3.3 hold. Then
\[ \|u_M - u_{e,M}\|_{CM} = O \left( \frac{\log M}{M^{2/3}} + |1 - \gamma^3 Ma^{2/3}mP| \right) \text{ as } M \to \infty, \]  
(102)
where \(u_M\) and \(u_{e,M}\) are defined in (61) and (80), respectively.

To get the rate of convergence (102) we have assumed that \(p(x) \in C^2(D)\). If \(p(x) \in C(D)\) then the rate given in Theorem 3.4 is no longer valid. The rate of \(\|u_M - u_{e,M}\|_{CM}\) when \(p(x) \in C(D)\) is given in the following theorem.

Theorem 3.5. Let Assumption A) hold and \(p \in C(D)\) satisfies
\[ |p(x) - p(y)| \leq \omega_p(|x - y|), \quad \forall x, y \in D, \]  
(103)
where \(\omega_p\) is the modulus of continuity of the function \(p(x)\). Then
\[ \|u_M - u_{e,M}\|_{CM} = O \left( \frac{\log M}{M^{1/3}} + \omega_p \left( \frac{1}{M^{1/3}} \right) \right) \]  
(104)
where \(u_M\) and \(u_{e,M}\) are defined in (61) and (80), respectively.

Proof. We have
\[ \|u_M - u_{e,M}\|_{CM} \leq \|u_M - \bar{u}_M\|_{CM} + \|\bar{u}_M - u_{e,M}\|_{CM}. \]  
(105)
Let us estimate \(\|u_M - \bar{u}_M\|_{CM}\). From (67) we have
\[ \|u_M - \bar{u}_M\|_{CM} \leq c_1 \|Tdu - T_{d,M}u_M\|_{CM}, \]  
(106)
where \(c_1\) is defined in (62). Using the similar steps given in (68) we get the following estimate for \(\|Tdu - T_{d,M}u_M\|_{CM}\):
\[ \|Tdu - T_{d,M}u_M\|_{CM} \leq \frac{3\|p\|_{\infty}\|u\|_{\infty}}{2(mP)^2} + I_1 + I_2, \]  
(107)
where \(I_1\) and \(I_2\) are defined in (69) and (70), respectively. It is shown in (72) that \(I_1 = O(1/M^{2/3})\). Since \(p(x) \in C(D)\), the steps (74)-(77) are no longer valid. The estimate of \(I_2\) can be derived as follows. Since \(p \in C(D)\) and \(u \in C^1(D)\), it follows from (70) that
\[ I_2 \leq \|p\|_{\infty}\|Du\|_{\infty} \max_{1 \leq i \leq M} \sum_{j=1, j \neq i}^{M} \int_{D_i} |g(x_i, y)||x_i - y|dy \]  
\[ \leq \frac{\sqrt{3}\|p\|_{\infty}\|Du\|_{\infty}}{2mP} \max_{1 \leq i \leq M} \int_{B_{\sqrt{|x_i|}}} \frac{1}{4\pi|x_i - y|}dy = O(1/(mP)) = O(1/M^{1/3}). \]  
(108)
This together with (107) and $I_1 = O(1/M^{2/3})$ yield

$$\|u_M - \tilde{u}_M\|_{C^0} = O(1/M^{1/3}).$$

(109)

Let us find an estimate for $\|\tilde{u}_M - u_{e,M}\|_{C^0}$. From (84) we have

$$\|\tilde{u}_M - u_{e,M}\|_{C^0} \leq c_1 \|T_e u_{e,M} - T_d u_{e,M}\|_{C^0},$$

(110)

where $c_1$ is defined in (52). By definitions (48) and (82), and use the triangle inequality, we get

$$\|T_e u_{e,M} - T_d u_{e,M}\|_{C^0} \leq J_1 + J_2,$$

(111)

where

$$J_1 := \max_{1 \leq l \leq M} \left| \int_{D_l} g(x_l, y)p(y)dy u_{e}(x_l)dy \right|,$$

(112)

and

$$J_2 := \max_{1 \leq l \leq M} \left| \sum_{j=1,j \neq l}^{M} \int_{D_j} (g(x_l, x_j)p_{a_m,p}(x_j) - g(x_l, y)p(y)) u_{e}(x_j)dy \right|,$$

(113)

$p_{a_m,p} := p(x)(\gamma_m P a^{(2-\kappa)/3})^3$. It is proved in (101) that $J_1 = O(1/M^{2/3})$. The estimate of $J_2$ is derived as follows. By the triangle inequality we obtain

$$J_2 \leq J_{2,1} + J_{2,2},$$

(114)

where

$$J_{2,1} := \max_{1 \leq l \leq M} \left| \sum_{j=1,j \neq l}^{M} \int_{D_j} (g(x_l, x_j) - g(x_l, y))p_{a_m,p}(x_j)u_{e}(x_j)dy \right|,$$

(115)

and

$$J_{2,2} := \max_{1 \leq l \leq M} \|u_{e}\|_{C^0} \sum_{j=1,j \neq l}^{M} \int_{D_j} |g(x_l, y)||p_{a_m,p}(x_j) - p(y)|dy.$$

(116)

It is proved in (111) that

$$J_{2,1} = O \left( \frac{\log M}{M^{2/3}} \right).$$

(117)
To estimate $J_{2,2}$, we apply the triangle inequality and get

\[
J_{2,2} \leq \| u_e \|_{CM} \max_{1 \leq l \leq M} \sum_{j=1, j \neq l}^{M} \int_{D_j} |g(x_l, y)||p_{a,mP}(x_j) - p(x_j)| dy
\]

\[
+ \| u_e \|_{CM} \max_{1 \leq l \leq M} \sum_{j=1, j \neq l}^{M} \int_{D_j} |g(x_l, y)||p(x_j) - p(y)| dy
\]

\[
\leq |\gamma^3 Ma_m^2 - \kappa| \| p \|_{\infty} \max_{1 \leq l \leq M} \| u_e \|_{CM} \sum_{j=1, j \neq l}^{M} \int_{D_j} |g(x_l, y)| dy
\]

\[
+ \max_{j} \sup_{y \in D_j} \omega_p(|x_j - y|) \| u_e \|_{CM} \max_{1 \leq l \leq M} \sum_{j=1, j \neq l}^{M} \int_{D_j} |g(x_l, y)| dy
\]

\[
= O \left( |\gamma^3 Ma_m^2 - \kappa| + \omega_p(1/M^{1/3}) \right),
\]

where $\omega_p$ is the modulus of continuity of $p(x)$. This together with $J_1 = O(1/M^{2/3})$ and (117) yield

\[
\| \tilde{u}_M - u_{e,M} \|_{CM} = O \left( \frac{\log M}{M^{2/3}} + |\gamma^3 Ma_m^2 - \kappa| + \omega_p(1/M^{1/3}) \right).
\]

Relation (118) follows from (105), (109) and (119). Theorem 3.5 is proved.

\[
\Box
\]

As we mentioned in the introduction, the main goal is to develop an algorithm for obtaining the minimal number of the embedded small balls which generate a material whose refraction coefficient differs from the desired one by not more than a desired small quantity. Let us derive an approximation of the desired refraction coefficient $n^2(x)$ generated by the embedded small balls. We rewrite the sum in (38) as

\[
\sum_{j=1}^{M} g(x, x_j)p_{a,mP}(x_j)u(x_j)|D_j|,
\]

where $|x - x_j| > a_{mP}$, $j = 1, 2, \ldots, M$, $|D_j| = 1/(mP)^3$ is the volume of the cube $D_j$, and

\[
p_{a,mP}(x) := 4\pi h(x)N(x)(\gamma m P a^{(2-\kappa)/3})^3, \quad N(x) = 1/\gamma^3.
\]

Since $(\gamma m P a^{(2-\kappa)/3})^3 \to 1$ as $m \to \infty$, it follows that (120) is a Riemannian sum for the integral $\int_{D_j} g(x, y)p(y)u(y)dy$, where $p(x) = 4\pi h(x)N(x)$. This motivates us to define the following approximation of the refraction coefficient $n^2(x)$:

\[
n_{a,mP}^2(x) := n_0^2(x) - k^2 p_{a,mP}(x),
\]

(122)
where \( p_{a_m^P} \) is defined in (121). We are interested in finding the largest radius \( a_{m^P} \) (or the smallest \( M = (mP)^3 \)) such that

\[
e(M) := \max_{1 \leq l \leq M} \left| n^2(x_l) - n^2_{a_{m^P}}(x_l) \right| \leq \epsilon/k^2 := \epsilon(k),
\]

where \( k \) is the wave number, \( \epsilon > 0 \) is a given small quantity and \( n^2_{a_{m^P}}(x) \) is defined in (122).

An estimate of the error \( e(M) \), defined in (123), is given in the following theorem.

**Theorem 3.6.** Suppose Assumption A) holds and \( N(x) = 1/\gamma^3 \). Then

\[
\max_{1 \leq l \leq (mP)^3} \left| n^2(x_l) - n^2_{a_{m^P}}(x_l) \right| \leq k^{-2} \| p \|_\infty \left| 1 - (\gamma mP a_{m^P}^{(2-\kappa)/3})^3 \right|,
\]

where \( x_l \) is the center of the \( l \)-th small ball, \( p(x) \) is defined in (11), \( n^2(x) = n_0^2(x) - k^{-2}p(x) \), and \( n^2_{a_{m^P}} \) is defined in (122). Consequently,

\[
\lim_{m \to \infty} \max_{1 \leq l \leq (mP)^3} \left| n^2(x_l) - n^2_{a_{m^P}}(x_l) \right| = 0.
\]

**Proof.** Let

\[
I_l := |n(x_l) - n^2_{a_{m^P}}(x_l)|.
\]

Then

\[
I_l \leq k^{-2} |p(x_l) - p(x_l)| \left| \gamma mP a_{m^P}^{(2-\kappa)/3} \right|^3 \leq k^{-2} \| p(x_l) \|_\infty \left| 1 - (\gamma mP a_{m^P}^{(2-\kappa)/3})^3 \right| \leq k^{-2} \| p \|_\infty \left| 1 - (\gamma mP a_{m^P}^{(2-\kappa)/3})^3 \right|.
\]

This together with relation (22) yield (125). Theorem 3.6 is proved. \( \square \)

Using Theorem 3.6 one can calculate the smallest \( M \) satisfying (123) by the following algorithm:

**Algorithm**

**Initializations:** Let the wave number \( k \), the constant \( \epsilon > 0 \), \( n_0^2(x) \) and \( n^2(x) \) be given. Fix \( P > 1 \), \( m = m_0 := 1 \), \( \kappa \in (0, 1) \), \( \gamma > [1/(2P)]^{(\kappa+1)/3} \) and \( N(x) = 1/\gamma^3 \). Partition \( D \) into \( P^3 \) cubes \( \Omega_q \), \( D = \bigcup_{q=1}^{P^3} \Omega_q \), \( \Omega_j \cap \Omega_i = \emptyset \) for \( j \neq i \), where each cube \( \Omega_j \) has side length \( 1/P \).

**Step 1.** Solve the equation

\[
\gamma a_{m^P}^{(2-\kappa)/3} + a_{m^P} - 1/(mP) = 0
\]

for \( a_{m^P} \).
Step 2. Embed \( m^3 \) small balls of radius \( a_{mP} \) in each cube \( \Omega_q \) so that Assumption A) holds.

Step 3. Compute
\[
p(x_l) = k^2(n_0^2(x_l) - n^2(x_l))
\]
and
\[
p_{a_{mP}}(x_l) = p(x_l)[\gamma m P a_{mP}^{(2-\kappa)/3}]^3, \quad l = 1, 2, \ldots, (mP)^3,
\]
where \( x_l \) is the center of the \( l \)-th small ball and \( k \) is the wave number.

Step 4. If \( \max_{1 \leq l \leq (mP)^3} |p(x_l) - p_{a_{mP}}(x_l)| > \epsilon \), then set \( m = m + 1 \) and go to Step 1. Otherwise the number \( M = (mP)^3 \) is the smallest number of the balls embedded in \( D \) such that inequality (123) holds, and \( a_{mP} \) is the radius of each embedded ball.

4 Numerical experiments

In this section we give the results of the numerical experiments. Suppose the refraction coefficient of the original material in \( D \) is \( n_0^2(x) = 1 \) and the desired refraction coefficients are:

Example 1. \( n^2(x) = 5 \),

Example 2. \( n^2(x) = 5 + \exp(-|x - x_0|^2/(2\sigma^2))/\sqrt{2\pi\sigma} \), where \( x_0 = (0.5, 0.5, 0.5) \) and \( \sigma = \sqrt{\frac{3}{2\\pi}} \). Here \( b \) is the smallest number \( m \) taken from Example 1.

Example 3. \( n^2(x) = 1 + 0.5 \sin(x_1) \), where \( x_1 \) is the first element of the vector \( x \),

Example 4. \( n^2(x) = 1 + 0.5 \sin(100x_1) \), where \( x_1 \) is the first element of the vector \( x \).

By the recipe we choose
\[
h(x) = k^2[n_0^2(x) - n^2(x)]/(4\pi N(x)) = \gamma^3 k^2(n_0^2(x) - n^2(x))/(4\pi), \quad k > 0. \tag{128}
\]

Let us take
\[
P = 11, \quad \kappa = 0.99, \quad \gamma = 10k[1/(2P)]^{(1+\kappa)/3}, \quad m_0 = 1, \tag{129}
\]
where \( k \geq 1 \) is the wave number and \( m_0 \) is the initial number of small balls described in the algorithm. Here the parameters \( P = 11 \) and \( m_0 = 1 \) are chosen so that the approximation error in Lemma 3.2 is at most \( c(k)10^{-4} \), where \( c(k) \) is a constant depending on the wave number \( k \). We apply the algorithm given in Section 3 to get the minimal total number of small balls embedded in the cube \( D \) such that inequality (123) holds for various values of \( \epsilon \), where the quantity \( \epsilon \) was defined in the Algorithm (see the Initialization and Step 4 of the Algorithm).
The smallest number of the balls embedded in $D$ increases as $\epsilon$ decreases. The radius $a_{mP}$ and the ratio $a_{mP}/d_{mP}$ decrease as $M$ increases, which agrees with the theory. The results are shown in tables 1-4. In these tables we define

$$d_{mP} := \min_{1 \leq i,j \leq M, i \neq j} \text{dist}(B_{a_{mP}}(x_i), B_{a_{mP}}(x_j)),$$

where $B_{a}(x)$ is defined in (19), and

$$E := \max_{1 \leq l \leq M} |n^2(x_l) - n_{a_{mP}}^2(x_l)|,$$

where $M$ is the smallest total number of small balls embedded in the domain $D$, $a_{mP}$ is the radius of the embedded small balls and $x_l$ is the center of the $l$-th small ball. In Example 1 we choose a constant refraction coefficient $n^2(x)$. For $k = 1$ the total number of small balls $M$ increases by $1.651 \times 10^5$ when the error level $\epsilon$ is decreased by 50%, while for $k = 5$ the value of $M$ increases by $3.4609 \times 10^4$ as the error level $\epsilon$ decreases by 50%, as shown in Table 1.

In Example 2 we add a Gaussian function to the constant refraction coefficient $n^2(x)$ considered in Example 1. For $k = 1$ the value of $M$ increases significantly as the error level $\epsilon$ decreases by 50%.

| $\epsilon$   | $m$     | $M$     | $a_{mP}$ | $a_{mP}/d_{mP}$ | $E$            |
|--------------|---------|---------|----------|-----------------|----------------|
| $5.000 \times 10^{-4}$ | 1       | $1.331 \times 10^5$ | $3.722 \times 10^{-4}$ | $5.445 \times 10^{-7}$ | $9.747 \times 10^{-2}$ |
| $5.000 \times 10^{-3}$ | 5       | $1.664 \times 10^5$ | $3.198 \times 10^{-6}$ | $1.098 \times 10^{-7}$ | $4.219 \times 10^{-3}$ |

Table 1: Example 1

| $\epsilon$   | $m$     | $M$     | $a_{mP}$ | $a_{mP}/d_{mP}$ | $E$            |
|--------------|---------|---------|----------|-----------------|----------------|
| $5.000 \times 10^{-4}$ | 1       | $1.331 \times 10^5$ | $3.200 \times 10^{-6}$ | $2.196 \times 10^{-7}$ | $8.448 \times 10^{-4}$ |
| $5.000 \times 10^{-3}$ | 3       | $3.594 \times 10^4$ | $1.225 \times 10^{-7}$ | $7.320 \times 10^{-4}$ | $9.701 \times 10^{-5}$ |

Table 2: Example 2

The refraction coefficients $n^2(x)$ considered in Examples 3 and 4 are periodic. In Example 3 for $k = 1$ the total number of the embedded small particles $M$ increases by 9319 as the error level $\epsilon$ decreases by 50%. A similar increment of $M$ is obtained for $k = 5$. These results are shown in Table 3.

In Example 4 the angular frequency of the sine function is 100 times the angular frequency of the sine function given in Example 3. In this case we get
significant increments of the value of $M$ as the error level $\epsilon$ decreases by 50% for the wave numbers $k = 1$ and 5, see Table 4.

| $\epsilon$      | $m$    | $M$    | $a_m P$ | $a_m P / d_m P$ | $E$     |
|------------------|--------|--------|---------|-----------------|---------|
| $5.00 \times 10^{-5}$ | 1      | $1.331 \times 10^5$ | $3.722 \times 10^{-4}$ | $5.445 \times 10^{-2}$ | $5.536 \times 10^{-4}$ |
| $5.00 \times 10^{-4}$ | 2      | $1.065 \times 10^4$  | $4.837 \times 10^{-5}$ | $2.739 \times 10^{-2}$ | $7.239 \times 10^{-5}$ |
| $5.00 \times 10^{-5}$ | 1      | $1.331 \times 10^5$ | $3.200 \times 10^{-6}$ | $2.196 \times 10^{-3}$ | $4.798 \times 10^{-6}$ |
| $5.00 \times 10^{-4}$ | 2      | $1.065 \times 10^4$  | $4.084 \times 10^{-7}$ | $1.098 \times 10^{-3}$ | $6.126 \times 10^{-7}$ |

Table 3: Example 3

| $\epsilon$      | $m$    | $M$    | $a_m P$ | $a_m P / d_m P$ | $E$     |
|------------------|--------|--------|---------|-----------------|---------|
| $5.00 \times 10^{-5}$ | 1      | $1.331 \times 10^5$ | $3.722 \times 10^{-4}$ | $5.445 \times 10^{-2}$ | $1.218 \times 10^{-2}$ |
| $5.00 \times 10^{-4}$ | 6      | $2.875 \times 10^5$  | $1.861 \times 10^{-6}$ | $9.147 \times 10^{-3}$ | $3.673 \times 10^{-4}$ |
| $5.00 \times 10^{-5}$ | 8      | $6.815 \times 10^5$  | $6.650 \times 10^{-9}$ | $2.745 \times 10^{-4}$ | $1.756 \times 10^{-6}$ |
| $5.00 \times 10^{-4}$ | 1      | $1.331 \times 10^5$ | $3.200 \times 10^{-6}$ | $2.196 \times 10^{-3}$ | $1.05 \times 10^{-4}$ |
| $5.00 \times 10^{-5}$ | 2      | $1.065 \times 10^4$  | $4.084 \times 10^{-7}$ | $1.098 \times 10^{-3}$ | $6.126 \times 10^{-7}$ |

Table 4: Example 4

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