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Quasi-local and frequency robust preconditioners for the Helmholtz first-kind integral equations on the disk

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Abstract

We propose preconditioners for the Helmholtz scattering problems by a planar, disk-shaped screen in \mathbb{R}^3 . Those preconditioners are approximations of the square-roots of some partial differential operators acting on the screen. Their matrix-vector products involve only a few sparse system resolutions and can thus be evaluated cheaply in the context of iterative methods. For the Laplace equation (i.e. for the wavenumber $k = 0$) with Dirichlet condition on the disk and on regular meshes, we prove that the preconditioned linear system has a bounded condition number uniformly in the mesh size. We further provide numerical evidence indicating that the preconditioners also perform well for large values of k and on locally refined meshes.

1 Introduction

We consider the problem of acoustic scattering by a disk-shaped screen

$$\mathbb{D} := \{x = (x_1, x_2, 0) \in \mathbb{R}^3 \text{ such that } |x|^2 := x_1^2 + x_2^2 < 1\}$$

in \mathbb{R}^3 , and its numerical simulation using the boundary element method (BEM). Calling $k \geq 0$ the wavenumber, with the convention that $k = 0$ for the Laplace equation, the problem can usually be rephrased as

$$V_k \lambda = f \text{ or } W_k \mu = g \tag{1}$$

depending whether one considers a Dirichlet or Neumann boundary condition on the disk \mathbb{D} . Here λ and μ respectively stand for the jumps of the Neumann and Dirichlet traces of the scattered field across \mathbb{D} , while the weakly singular operator $V_k : \tilde{H}^{-1/2}(\mathbb{D}) \rightarrow H^{1/2}(\mathbb{D})$ and the hypersingular operator $W_k : \tilde{H}^{1/2}(\mathbb{D}) \rightarrow H^{-1/2}(\mathbb{D})$ are defined by

$$V_k \varphi := \int_{\mathbb{D}} G_k(x-y) \varphi(y) d\sigma(y), \quad W_k \varphi := \oint_{\mathbb{D}} \frac{\partial^2}{\partial n_x \partial n_y} G_k(x-y) \varphi(y) d\sigma(y), \tag{2}$$

with $G_k(x) := \frac{e^{ik|x|}}{4\pi|x|}$ (the precise definitions are given in Section 3). Having computed λ or μ , the scattered field is finally explicitly obtained on $\mathbb{R}^3 \setminus \mathbb{D}$ through a classical representation formula (see e.g. [12, 33]).

Solving the problem with the BEM involves the resolution of linear systems with the matrices \mathbf{V}_k or \mathbf{W}_k defined by

$$(\mathbf{V}_k)_{i,j} := \langle V_k \varphi_j, \varphi_i \rangle \quad \text{and} \quad (\mathbf{W}_k)_{i,j} := \langle W_k \psi_j, \psi_i \rangle, \quad 1 \leq i, j \leq N_{dof},$$

where the boundary element basis $\{\varphi_i\}_{1 \leq i \leq N_{dof}} \subset \tilde{H}^{-1/2}(\mathbb{D})$ and $\{\psi_i\}_{1 \leq i \leq N_{dof}} \subset \tilde{H}^{1/2}(\mathbb{D})$ are sets of functions defined on a mesh of the screen \mathbb{D} , and the brackets stand for the duality products in $\tilde{H}^{-1/2}(\mathbb{D}) \times H^{1/2}(\mathbb{D})$ and $H^{-1/2}(\mathbb{D}) \times \tilde{H}^{1/2}(\mathbb{D})$ respectively. In the boundary element method, due to the non-local structure of the Green kernel G_k , the matrices \mathbf{V}_k and \mathbf{W}_k are fully populated, preventing a priori the use of fine meshes on the scatterer. However, in the past thirty years, several acceleration methods (e.g. the Fast Multipole Method [19, 37], and H-Matrices [20]) have been developed that enable to compute the matrix-vector products $x \mapsto \mathbf{V}_k x, \mathbf{W}_k x$ in quasi-linear complexity. This allows to use iterative solvers for solving the underlying linear systems.

Nevertheless, when the problem of scattering by a bidimensional screen is considered, several difficulties still appear:

- The solutions of the integral equations have a well-known singularity at the edge of the screen (see e.g. [13]). In order to capture this singularity, the mesh needs to be refined locally near this edge [26].
- The condition number of the matrices \mathbf{V}_k and \mathbf{W}_k increases when the mesh is getting finer and this effect is aggravated by local mesh refinements, see e.g. [18].

Although preconditioning techniques for integral equations is a well established subject (see for instance [4, 5, 11, 39] and references therein), the extension of those ideas to singular domains has only been considered recently, e.g. by the authors in [3] (see also [10, 17, 23, 25]). The first goal of this work is to generalize the approach of [3] for 3D scattering problems on the disk \mathbb{D} by introducing preconditioners that are robust both with respect to the mesh parameters and the wavenumber k .

By now, there is a well established strategy to ensure robustness with respect to the mesh parameters. For example, in the case of the operator V_k , it is sufficient to find an isomorphism $P : H^{1/2}(\mathbb{D}) \rightarrow \tilde{H}^{-1/2}(\mathbb{D})$, together with a ‘‘stable discretisation’’ (see Section 4), to define a preconditioning matrix $\hat{\mathbf{P}}$ associated to P . Then, it can be shown that the condition number of $\hat{\mathbf{P}}\mathbf{V}_k$ is bounded by a constant that depends on k and P , but is otherwise independent of the mesh width. This property is often referred to as optimal preconditioning.

Nevertheless, being an optimal preconditioner only means that the condition number stays stable with respect to mesh refinements while k is held fixed. There is no expected behavior when one considers different – and more specifically high – wave numbers. Classical optimal preconditioners constructed for the Laplace equation ($k = 0$) behave poorly at high frequency in practice.

To counteract this negative behavior, our second objective is thus to propose a family of operators $(P_k)_{k>0}$, that depend on the wavenumber k , such that the iterative resolution of the linear system associated to the matrix $\hat{\mathbf{P}}_k \mathbf{V}_k$ involves a small number of iterations for a large range of values of k . Unfortunately, we are not aware of a general theory to estimate the number of iterations uniformly with respect to k (not even in the more favourable case of the scattering by a smooth surface without boundary), so for the time being, we must rely on numerical experiments to demonstrate the efficiency of the strategy.

Let us now briefly outline the contents of this paper. Introducing the weight

$$\omega(x) := \sqrt{1 - x_1^2 - x_2^2}, \quad \text{for } x \in \mathbb{D}, \quad (3)$$

the main result of the paper is that

$$P_0 := \frac{1}{\omega} \left(-\omega \operatorname{div} \omega \nabla + \frac{1}{4} \operatorname{Id} \right)^{\frac{1}{2}}, \quad Q_0 := \omega (-\operatorname{div} \omega \nabla \omega)^{-\frac{1}{2}}$$

are spectrally equivalent to V_0^{-1} , and W_0^{-1} , respectively. Above and in what follows, Id stands for the identity operator, and $\omega \operatorname{div} \omega \nabla$ and $\operatorname{div} \omega \nabla \omega$ are understood as

$$(\omega \operatorname{div} \omega \nabla) u(x) = \omega(x) \operatorname{div}(\omega(x) \nabla u(x)), \quad (\operatorname{div} \omega \nabla \omega) u(x) = \operatorname{div}(\omega(x) \nabla(\omega(x) u(x))). \quad (4)$$

In other words, ω represents the multiplicative operator $(\omega u)(x) := \omega(x)u(x)$. The operators P_0 and Q_0 provide us with isomorphisms $H^{-1/2}(\mathbb{D}) \rightarrow \tilde{H}^{-1/2}(\mathbb{D})$ and $H^{-1/2}(\mathbb{D}) \rightarrow \tilde{H}^{1/2}(\mathbb{D})$ that, as we shall see, are cheaply evaluated when it comes to Galerkin discretization, and can be used efficiently as preconditioners for V_0 and W_0 respectively.

In order to proceed we introduce in Section 2 a scale of Hilbert spaces that conveniently replaces the classical Sobolev scale. This generalizes to the case of the disk in 3D, the scale introduced in [3] for open curves in 2D. Section 3 is then devoted to show the claimed result, i.e. the spectral equivalence of V_0^{-1} and P_0 on the one hand and W_0^{-1} and Q_0 on the other hand. For $k > 0$, our previous work [3] in dimension 2 suggests to generalize the preceding operators as :

$$P_k := \frac{1}{\omega} (-\omega \operatorname{div} \omega \nabla - k^2 \omega^2)^{\frac{1}{2}}, \quad Q_k := \omega (-\operatorname{div} \omega \nabla \omega - k^2 \omega^2)^{-\frac{1}{2}}.$$

The details on the Galerkin discretization, the efficient computation of the square roots, and the proofs of the uniform estimates of the condition number with respect to the mesh parameters are provided in Section 4. Eventually, the performance of the proposed preconditioners are reported in Section 5, and the implementation is openly available [7].

2 Weighted functional analysis on the disk

We now introduce some Hilbert scales \mathcal{T}^s and \mathcal{U}^s of functions on \mathbb{D} that are weighted versions of Sobolev spaces especially well suited for the analysis of the considered problem. In those scales, the operators $-\omega \operatorname{div} \omega \nabla$ and $-\operatorname{div} \omega \nabla \omega$ are positive self-adjoint, allowing to define their square roots, which are the main ingredient in our preconditioning strategy.

We start by introducing $L_{\frac{1}{\omega}}^2$ and L_{ω}^2 the weighted L^2 spaces defined by

$$L_{\frac{1}{\omega}}^2 := \left\{ u \in L_{loc}^1(\mathbb{D}, \mathbb{C}) \mid \|u\|_{\frac{1}{\omega}}^2 := \int_{\mathbb{D}} \frac{|u(x)|^2}{\omega(x)} dx < +\infty \right\},$$

$$L_{\omega}^2 := \left\{ u \in L_{loc}^1(\mathbb{D}, \mathbb{C}) \mid \|u\|_{\omega}^2 := \int_{\mathbb{D}} \omega(x) |u(x)|^2 dx < +\infty \right\},$$

with ω given by Eq. (3).

Those spaces, when equipped with the respective scalar products

$$\forall (u, v) \in (L_{\frac{1}{\omega}}^2)^2, \quad (u, v)_{\frac{1}{\omega}} := \int_{\mathbb{D}} \frac{u(x) \overline{v(x)}}{\omega(x)} dx,$$

$$\forall (u, v) \in (L_\omega^2)^2, \quad (u, v)_\omega := \int_{\mathbb{D}} \omega(x) u(x) \overline{v(x)} dx,$$

are Hilbert spaces.

Complete orthogonal families of these spaces are given by the following Proposition (see [35, 24]).

Proposition 1. *Let $\Lambda = \{(l, m) \in \mathbb{N} \times \mathbb{Z} \mid -l \leq m \leq l \text{ and } l - m \text{ is even}\}$, and let T_l^m and U_l^m be the functions defined for $(l, m) \in \Lambda$ and $x = (\rho, \varphi)$ by*

$$T_l^m(x) = Y_l^m(\arcsin(\rho), \varphi) \text{ and } U_l^m(x) = \frac{Y_{l+1}^m(\arcsin(\rho), \varphi)}{\omega(x)}$$

where the function $Y_l^m(\theta, \varphi)$, $(\theta, \varphi) \in [0, \pi] \times [0, 2\pi)$ are the classical spherical harmonics. The set $\{T_l^m\}_{(l,m) \in \Lambda}$ (resp. $\{U_l^m\}_{(l,m) \in \Lambda}$) is a complete orthogonal family of L_ω^2 (resp. L_ω^2). The functions T_l^m and U_l^m satisfy in particular for all (l_1, m_1) and (l_2, m_2) in Λ ,

$$\int_{\mathbb{D}} \frac{T_{l_1}^{m_1}(x) \overline{T_{l_2}^{m_2}(x)}}{\omega(x)} dx = \frac{1}{2} \delta_{l_1=l_2} \delta_{m_1=m_2}, \quad \int_{\mathbb{D}} \omega(x) U_{l_1}^{m_1}(x) \overline{U_{l_2}^{m_2}(x)} dx = \frac{1}{2} \delta_{l_1=l_2} \delta_{m_1=m_2}. \quad (5)$$

The functions T_l^m and U_l^m enjoy further properties. We provide the reader with a few of them that will turn out to prove useful in the following. Spherical harmonics are the restriction to the sphere of harmonic homogeneous polynomials in (x_1, x_2, x_3) . Using this convention, one can write Y_l^m as

$$\begin{aligned} Y_l^m(x_1, x_2, x_3) &= \eta_l^m e^{im\phi} P_l^m(x_3) \\ &= \eta_l^m (x_1 + ix_2)^m \frac{d^{l+m}}{dt^{l+m}} [(t^2 - 1)^l]_{|t=x_3}, \end{aligned}$$

where $\eta_l^m = (-1)^m \sqrt{\frac{(2l+1)(l-m)!}{4\pi(l+m)!}}$ is a normalization coefficient that ensures $\int_{\mathbb{S}^2} |Y_l^m|^2 d\sigma = 1$, $(x_1, x_2) = (\rho \cos(\phi), \rho \sin(\phi))$ and P_l^m stand for the associated Legendre polynomials.

Using that, on the sphere, we have $x_3^2 = 1 - x_1^2 - x_2^2 = \omega(x)^2$, we can rewrite the spherical harmonics as polynomials for which the degree in the x_3 variables does not exceed 1. The T_l^m are obtained from the spherical harmonics that have a degree 0 in x_3 , while the U_l^m are the ones obtained from the spherical harmonics of degree exactly 1 in x_3 . Consequently, we deduce that the functions T_l^m and U_l^m are polynomial functions in (x_1, x_2) , and a closer analysis shows that their degree is precisely l . We therefore deduce the following lemma, denoting by $C^\infty(\mathbb{D})$ the set of restrictions to \mathbb{D} of functions in $C^\infty(\mathbb{R}^2)$.

Lemma 1. *For all $(l, m) \in \Lambda$, the functions T_l^m and U_l^m are in $C^\infty(\mathbb{D})$.*

A uniform bound can also be obtained by noticing that the spherical harmonics Y_l^m satisfy the addition formula

$$\sum_{m=-l}^l Y_l^m(\theta, \varphi) \overline{Y_l^m(\theta', \varphi')} = \frac{2l+1}{4\pi} P_l(a \cdot a')$$

where $P_l = P_l^0$ is the Legendre polynomial of degree l and a and a' are the points of the sphere with spherical coordinates (θ, φ) and (θ', φ') respectively. Applying this identity for $a = a' =$

$(\rho \cos(\varphi), \rho \sin(\varphi), \sqrt{1 - \rho^2})$, and since $P_l(1) = 1$, we conclude that for any $x = (\rho \cos(\varphi), \rho \sin(\varphi), 0) \in \mathbb{D}$, and for any $l \in \mathbb{N}$,

$$\sum_{\substack{m=-l \\ m-l \text{ even}}}^l |T_l^m(x)|^2 \leq \sum_{m=-l}^l |Y_l^m(\arcsin \rho, \varphi)|^2 = \frac{2l+1}{4\pi}.$$

In particular, this implies the bound, $\forall x \in \mathbb{D}, \forall (l, m) \in \Lambda$,

$$|T_l^m(x)| \leq \sqrt{\frac{2l+1}{4\pi}}. \quad (6)$$

As a consequence of Proposition 1, any function $u \in L_{\frac{1}{\omega}}^2$ and $v \in L_{\omega}^2$ may be expanded in a Fourier-like series as

$$u(x) = \sum_{(l,m) \in \Lambda} \hat{u}_l^m T_l^m(x), \quad v(x) = \sum_{(l,m) \in \Lambda} \check{v}_l^m U_l^m(x),$$

where the series are converging in $L_{\frac{1}{\omega}}^2$ and L_{ω}^2 , respectively, and

$$\forall (l, m) \in \Lambda, \quad \hat{u}_l^m = 2 \int_{\mathbb{D}} \frac{u(x) \overline{T_l^m(x)}}{\omega(x)} dx, \quad \check{v}_l^m = 2 \int_{\mathbb{D}} \omega(x) v(x) \overline{U_l^m(x)} dx.$$

The following Parseval equalities also hold:

$$\int_{\mathbb{D}} \frac{|u(x)|^2}{\omega(x)} dx = \frac{1}{2} \sum_{(l,m) \in \Lambda} |\hat{u}_l^m|^2, \quad \int_{\mathbb{D}} \omega(x) |v(x)|^2 dx = \frac{1}{2} \sum_{(l,m) \in \Lambda} |\check{v}_l^m|^2. \quad (7)$$

We now use the following key lemma that enables us to define a scales of Hilbert spaces, comparable to the Sobolev spaces.

Lemma 2. *For all $(l, m) \in \mathbb{N} \times \mathbb{Z}$ such that $-l \leq m \leq l$, there holds*

$$-(\omega \operatorname{div} \omega \nabla) T_l^m = [l(l+1) - m^2] T_l^m, \quad (8)$$

$$-(\operatorname{div} \omega \nabla \omega) U_l^m = [(l+1)(l+2) - m^2] U_l^m. \quad (9)$$

We stress that the operators appearing on the left hand sides are understood as in Eq. (4).

Proof. One possible way to prove this lemma, is to introduce the projected moments \mathcal{L}_+ and \mathcal{L}_- , defined for a regular enough function u defined on \mathbb{D} by

$$\mathcal{L}_{\pm} u(\rho, \varphi) := e^{\pm i\varphi} \left(\pm \frac{\partial u}{\partial \rho} + i \frac{1}{\rho} \frac{\partial u}{\partial \varphi} \right).$$

Furthermore, we denote by $\omega \mathcal{L}_{\pm} \omega : C^{\infty}(\overline{\mathbb{D}}) \rightarrow C^{\infty}(\overline{\mathbb{D}})$ the operator defined by

$$(\omega \mathcal{L}_{\pm} \omega) \varphi(x) := \omega(x) \mathcal{L}_{\pm} (\omega(x) \varphi(x)) = \omega^2(x) \mathcal{L}_{\pm} \varphi(x) \mp \rho e^{\pm i\varphi} u(x).$$

Those operators are studied in [35], and their properties can be rephrased in our notation as follows: for all $(l, m) \in \Lambda$,

$$\mathcal{L}_\pm T_l^m = \sqrt{l(l+1) - m^2 \mp m} U_{l-1}^{m\pm 1}, \quad (10)$$

$$\omega \mathcal{L}_\pm \omega U_l^m = \sqrt{(l+1)(l+2) - m^2 \mp m} T_{l+1}^{m\pm 1}. \quad (11)$$

One easily checks that

$$\nabla = \frac{1}{2} \begin{pmatrix} \mathcal{L}_+ - \mathcal{L}_- \\ -i\mathcal{L}_+ - i\mathcal{L}_- \end{pmatrix}, \quad \omega \nabla \omega = \frac{1}{2} \begin{pmatrix} \omega \mathcal{L}_+ \omega - \omega \mathcal{L}_- \omega \\ -i\omega \mathcal{L}_+ \omega - i\omega \mathcal{L}_- \omega \end{pmatrix}, \quad (12)$$

which leads to the identities

$$\omega \operatorname{div} \omega \nabla = -\frac{(\omega \mathcal{L}_+ \omega) \mathcal{L}_- + (\omega \mathcal{L}_- \omega) \mathcal{L}_+}{2},$$

$$\operatorname{div} \omega \nabla \omega = -\frac{\mathcal{L}_+(\omega \mathcal{L}_- \omega) + \mathcal{L}_-(\omega \mathcal{L}_+ \omega)}{2},$$

and the result follows from Eqs. (10) and (11). \square

Definition 1 (Function spaces \mathcal{T}^s and \mathcal{U}^s). *Let \mathcal{T} and \mathcal{U} be the complex vector spaces of formal series*

$$\mathcal{T} = \left\{ \sum_{(l,m) \in \Lambda} \hat{u}_l^m T_l^m \mid (\hat{u}_l^m)_{(l,m) \in \Lambda} \in \mathbb{C}^\Lambda \right\}, \quad \mathcal{U} = \left\{ \sum_{(l,m) \in \Lambda} \check{v}_l^m U_l^m \mid (\check{v}_l^m)_{(l,m) \in \Lambda} \in \mathbb{C}^\Lambda \right\}.$$

For all $s \in \mathbb{R}$, we define the following Hilbert spaces:

$$\mathcal{T}^s := \{u \in \mathcal{T} \mid \|u\|_{\mathcal{T}^s} < \infty\}, \quad \mathcal{U}^s := \{v \in \mathcal{U} \mid \|v\|_{\mathcal{U}^s} < \infty\},$$

where

$$\|u\|_{\mathcal{T}^s}^2 := \frac{1}{2} \sum_{(l,m) \in \Lambda} |\hat{u}_l^m|^2 \left(\frac{1}{4} + l(l+1) - m^2 \right)^s, \quad \|v\|_{\mathcal{U}^s}^2 := \frac{1}{2} \sum_{(l,m) \in \Lambda} |\check{v}_l^m|^2 ((l+1)(l+2) - m^2)^s.$$

Note that, when $s \geq t$, $\mathcal{T}^s \subset \mathcal{T}^t$ and $\mathcal{U}^s \subset \mathcal{U}^t$. We adopt the notation

$$\mathcal{T}^{-\infty} := \bigcup_{s \in \mathbb{R}} \mathcal{T}^s, \quad \mathcal{T}^\infty := \bigcap_{s \in \mathbb{R}} \mathcal{T}^s, \quad \mathcal{U}^{-\infty} := \bigcup_{s \in \mathbb{R}} \mathcal{U}^s, \quad \mathcal{U}^\infty := \bigcap_{s \in \mathbb{R}} \mathcal{U}^s.$$

For $s \geq 0$, the convergent series in \mathcal{T}^s and \mathcal{U}^s are identified to their limits in $L^2_{\frac{1}{\omega}}(\mathbb{D})$ and $L^2_\omega(\mathbb{D})$ respectively, and in this case, one has

$$\hat{u}_l^m = \int_{\mathbb{D}} \frac{u(x) \overline{T_l^m(x)}}{\omega(x)} dx, \quad \check{v}_l^m = \int_{\mathbb{D}} \omega(x) v(x) \overline{U_l^m(x)} dx. \quad (13)$$

In this sense, $L^2_{\frac{1}{\omega}} \subset \mathcal{T}^s$ and $L^2_\omega \subset \mathcal{U}^s$ for all $s \leq 0$. Note that for $(u, v) \in L^2_{\frac{1}{\omega}} \times L^2_\omega$

$$\widehat{\bar{u}}_l^m = (-1)^m \overline{\hat{u}_l^m}, \quad \widetilde{\bar{u}}_l^m = (-1)^m \overline{\check{u}_l^m},$$

and this is taken as the definition of the complex conjugation on \mathcal{T}^s and \mathcal{U}^s .

Notice the factor $\frac{1}{4}$ in the definition of the \mathcal{T}^s norm and space that is conveniently taken for a reason that will appear clearer later (see Lemma 10). The following lemma shows that $C^\infty(\overline{\mathbb{D}})$ is a subset of \mathcal{T}^s and \mathcal{U}^s for all $s \in \mathbb{R}$:

Lemma 3. *Let $u \in C^\infty(\overline{\mathbb{D}})$ and $s \in \mathbb{R}$. Then $u \in \mathcal{U}^s$ and there exists $C_s > 0$ and $N_s \in \mathbb{N}$ such that*

$$\|u\|_{\mathcal{U}^s} \leq C_s \max_{|\alpha| \leq N_s} \|\partial^\alpha u\|_{L^\infty(\overline{\mathbb{D}})}$$

where $\alpha = (\alpha_1, \alpha_2) \in \mathbb{N}^2$ is a multi-index, $|\alpha| := \alpha_1 + \alpha_2$ and $\partial^\alpha u = \partial_{x_1}^{\alpha_1} \partial_{x_2}^{\alpha_2}$. The same statement holds replacing \mathcal{U}^s by \mathcal{T}^s .

Proof. Let $u \in C^\infty(\overline{\mathbb{D}})$. We remark that $u \in L_\omega^2$ and therefore

$$\check{u}_l^m = 2 \int_{\mathbb{D}} \omega(x) u(x) \overline{U_l^m(x)} dx$$

is well-defined. Now, noticing that

$$U_l^m(x) = \frac{-1}{((l+1)(l+2) - m^2)} [(\operatorname{div} \omega \nabla \omega) U_l^m](x)$$

and using the previous equality, an integration by parts gives

$$\check{u}_l^m = \frac{-2}{((l+1)(l+2) - m^2)} \int_{\mathbb{D}} \omega(x) [(\operatorname{div} \omega \nabla \omega) u](x) \overline{U_l^m(x)} dx,$$

where we have used that ω vanishes on $\partial\mathbb{D}$ to suppress the boundary terms.

This argument can be repeated to obtain, for any $p \in \mathbb{N}$,

$$\check{u}_l^m = (-1)^p \frac{2}{((l+1)(l+2) - m^2)^p} \int_{\mathbb{D}} \omega(x) [(\operatorname{div} \omega \nabla \omega)^p u](x) \overline{U_l^m(x)} dx.$$

We now remark that $\nabla \omega = \frac{x}{\omega}$, which entails that, for u regular enough,

$$(\operatorname{div} \omega \nabla \omega) u(x) = 2u(x) - x \cdot \nabla u(x) + \omega^2(x) \Delta u(x).$$

A simple reasoning by induction shows that $(\operatorname{div} \omega \nabla \omega)^p$ is a partial differential operator of the form

$$(\operatorname{div} \omega \nabla \omega)^p = \sum_{|\alpha| \leq 2p} c_\alpha(x) \partial^\alpha,$$

where, for all multi-index α such that $|\alpha| \leq 2p$, $c_\alpha \in C^\infty(\overline{\mathbb{D}})$. (In fact, the coefficients c_α are polynomials in x .) Thus for all p , there exists a constant $K_p > 0$ such that

$$|\check{u}_l^m| \leq \frac{K_p \max_{|\alpha| \leq 2p} \|\partial^\alpha u\|_{L^\infty(\mathbb{D})}}{((l+1)(l+2) - m^2)^p}.$$

For any $s \in \mathbb{R}$, we may take p sufficiently large to ensure that

$$K_s := \sum_{(l,m) \in \Lambda} ((l+1)(l+2) - m^2)^{s-2p} < +\infty.$$

We thus deduce that $u \in \mathcal{U}^s$ and

$$\|u\|_{\mathcal{U}^s} \leq C_s \max_{|\alpha| \leq 2p} \|\partial^\alpha u\|_{L^\infty(\overline{\mathbb{D}})}$$

where $C_s = \sqrt{K_s} K_p$. With the same method of proof, one can show the analogous result for \mathcal{T}^s . \square

It is easy to check that the sequence of truncated series of an element of \mathcal{T}^s or \mathcal{U}^s converges to this element in the same space. Hence the set of finite linear combinations of $\{T_l^m\}_{(l,m) \in \Lambda}$ (resp. $\{U_l^m\}_{(l,m) \in \Lambda}$) is dense in \mathcal{T}^s (resp. \mathcal{U}^s) for all $s \in \mathbb{R}$. It follows from this, Lemma 3 and Lemma 1 that $C^\infty(\overline{\mathbb{D}})$ is also dense in \mathcal{T}^s and \mathcal{U}^s for all real s .

Lemma 4. *For all $s' < s$, the inclusions $\mathcal{T}^s \subset \mathcal{T}^{s'}$ and $\mathcal{U}^s \subset \mathcal{U}^{s'}$ are compact and dense.*

Proof. The fact that the inclusions are dense follows from the previous remark. Let us show the claim concerning the compact inclusion $\mathcal{T}^s \subset \mathcal{T}^{s'}$. The proof of the result for the spaces \mathcal{U}^s goes along similar lines. Let $s \in \mathbb{R}$ and $s' = s - \delta$ for some $\delta > 0$. We have to show that \mathcal{T}^s is compactly embedded in $\mathcal{T}^{s-\delta}$, or equivalently, that if $(u^n)_n$ is a sequence that weakly converges to 0 in \mathcal{T}^s , then $(u^n)_n$ strongly converges to 0 in $\mathcal{T}^{s-\delta}$. Writing

$$u^n = \sum_{(l,m) \in \Lambda} (\hat{u}_l^m)^n T_l^m,$$

the weak \mathcal{T}^s convergence entails that both the following statements hold:

$$\exists C > 0, \forall n \in \mathbb{N}, \quad \|u^n\|_{\mathcal{T}^s}^2 = \sum_{(l,m) \in \Lambda} \left(\frac{1}{4} + l(l+1) - m^2 \right)^s |(\hat{u}_l^m)^n|^2 < C, \quad (14)$$

$$\forall (l,m) \in \Lambda, \quad \lim_{n \rightarrow +\infty} (\hat{u}_l^m)^n = 0. \quad (15)$$

Now, let $\varepsilon > 0$ and $L(\varepsilon) \in \mathbb{N}$ be such that

$$\left(\frac{1}{4} + L(\varepsilon) \right)^{-\delta} \leq \varepsilon, \quad (16)$$

we infer, noticing that, for all $(l,m) \in \Lambda$, $\frac{1}{4} + l(l+1) - m^2 \geq \frac{1}{4} + l$,

$$\begin{aligned} \|u^n\|_{\mathcal{T}^{s-\delta}}^2 &= \sum_{(l,m) \in \Lambda} \left(\frac{1}{4} + l(l+1) - m^2 \right)^{s-\delta} |(\hat{u}_l^m)^n|^2 \\ &= \sum_{(l,m) \in \Lambda, l \leq L(\varepsilon)} \left(\frac{1}{4} + l(l+1) - m^2 \right)^{s-\delta} |(\hat{u}_l^m)^n|^2 \\ &\quad + \sum_{(l,m) \in \Lambda, l \geq L(\varepsilon)+1} \left(\frac{1}{4} + l(l+1) - m^2 \right)^{s-\delta} |(\hat{u}_l^m)^n|^2 \\ &\leq \sum_{(l,m) \in \Lambda, l \leq L(\varepsilon)} \left(\frac{1}{4} + l(l+1) - m^2 \right)^{s-\delta} |(\hat{u}_l^m)^n|^2 + C\varepsilon \end{aligned}$$

using (14) and (16). By Eq. (15), we can now take n sufficiently large so that the first sum is smaller than ε , concluding the proof. \square

Lemma 5. For each $s \in \mathbb{R}$, the inner products $(\cdot, \cdot)_\omega$ and $(\cdot, \cdot)_\omega^\perp$ extend continuously to sesquilinear forms $\mathcal{U}^s \times \mathcal{U}^{-s}$ and $\mathcal{T}^s \times \mathcal{T}^{-s}$ respectively, and those extensions satisfy

$$\forall (u, v) \in \mathcal{U}^s \times \mathcal{U}^{-s}, \quad (u, v)_\omega = \frac{1}{2} \sum_{(l,m) \in \Lambda} \check{u}_l^m \overline{\check{v}_l^m}, \quad (17)$$

$$\forall (u, v) \in \mathcal{T}^s \times \mathcal{T}^{-s}, \quad (u, v)_\omega^\perp = \frac{1}{2} \sum_{(l,m) \in \Lambda} \hat{u}_l^m \overline{\hat{v}_l^m}. \quad (18)$$

Proof. First, if u and v are finite linear combinations of the functions $(U_l^m)_{(l,m) \in \Lambda}$, then it follows immediately from Eqs. (5) and (13) that

$$(u, v)_\omega = \frac{1}{2} \sum_{(l,m) \in \Lambda} \check{u}_l^m \overline{\check{v}_l^m}.$$

By density of such finite linear combinations in \mathcal{U}^s , it only remains to prove that the sesquilinear map

$$(u, v) \in \mathcal{U}^s \times \mathcal{U}^{-s} \mapsto \frac{1}{2} \sum_{(l,m) \in \Lambda} \check{u}_l^m \overline{\check{v}_l^m}$$

is continuous. This is indeed the case by the Cauchy-Schwarz inequality:

$$\begin{aligned} \left| \sum_{(l,m) \in \Lambda} \check{u}_l^m \overline{\check{v}_l^m} \right|^2 &\leq \sum_{(l,m) \in \Lambda} ((l+1)(l+2) - m^2)^s |\check{u}_l^m|^2 \sum_{(l,m) \in \Lambda} ((l+1)(l+2) - m^2)^{-s} |\check{v}_l^m|^2 \\ &= \|u\|_{\mathcal{U}^s}^2 \|v\|_{\mathcal{U}^{-s}}^2. \end{aligned}$$

The proof concerning the second inner product is similar. □

Lemma 6. For every $s \in \mathbb{R}$, the maps $\frac{1}{\omega} : \mathcal{T}^{-s} \rightarrow (\mathcal{T}^s)'$ and $\omega : \mathcal{U}^{-s} \rightarrow (\mathcal{U}^s)'$, defined by

$$\forall (u, v) \in \mathcal{T}^{-s} \times \mathcal{T}^s \quad \left(\frac{1}{\omega} u \right) (v) := (u, \bar{v})_\omega^\perp, \quad \forall (u, v) \in \mathcal{U}^{-s} \times \mathcal{U}^s, \quad (\omega u)(v) := (u, \bar{v})_\omega,$$

are bijective isometries. With a slight abuse of notation, we also denote $\omega = \left(\frac{1}{\omega}\right)^{-1} : (\mathcal{T}^s)' \rightarrow \mathcal{T}^{-s}$.

The proof, mainly relying on the Riesz theorem, presents no difficulty, so we omit it.

Lemma 7. For every $s \in \mathbb{R}$, the operators

$$\nabla : C^\infty(\overline{\mathbb{D}}) \rightarrow (C^\infty(\overline{\mathbb{D}}))^2, \quad \text{div} : (C^\infty(\overline{\mathbb{D}}))^2 \rightarrow C^\infty(\overline{\mathbb{D}}),$$

have unique extensions as linear continuous maps

$$\nabla : \mathcal{T}^s \rightarrow (\mathcal{U}^{s-1})^2, \quad \text{div} : (\mathcal{T}^s)^2 \rightarrow \mathcal{U}^{s-1}.$$

Proof. We perform the proof for the operator ∇ , the other being similar. First, if such a linear continuous extension exists, it is unique by density of $C^\infty(\mathbb{D})$ in \mathcal{T}^s for all $s \in \mathbb{R}$. For $u \in C^\infty(\mathbb{D})$ and $j \in \{1, 2\}$, let $v = \partial_{x_j} u \in L_\omega^2$. Using integration by parts and the identities (11)-(12), we find

$$\begin{aligned} \check{v}_l^m &= (\partial_{x_j} u, U_l^m)_\omega \\ &= - (u, (\omega \partial_{x_j} \omega) U_l^m)_\omega \\ &= \frac{1}{2} \begin{cases} -\sqrt{(l+1)(l+2) - m^2 - m} (u, T_{l+1}^{m+1})_\omega + \sqrt{(l+1)(l+2) - m^2 + m} (u, T_{l+1}^{m-1})_\omega & \text{if } j = 1, \\ i\sqrt{(l+1)(l+2) - m^2 - m} (u, T_{l+1}^{m+1})_\omega + i\sqrt{(l+1)(l+2) - m^2 + m} (u, T_{l+1}^{m-1})_\omega & \text{if } j = 2, \end{cases} \\ &= \frac{1}{4} \begin{cases} -\sqrt{(l+1)(l+2) - m^2 - m} \hat{u}_{l+1}^{m+1} + \sqrt{(l+1)(l+2) - m^2 + m} \hat{u}_{l+1}^{m-1} & \text{if } j = 1, \\ i\sqrt{(l+1)(l+2) - m^2 - m} \hat{u}_{l+1}^{m+1} + i\sqrt{(l+1)(l+2) - m^2 + m} \hat{u}_{l+1}^{m-1} & \text{if } j = 2, \end{cases} \end{aligned}$$

Naturally, we use this expression as a definition for $\partial_{x_j} u$ when $u \in \mathcal{T}^{-\infty}$. Using simple estimates, such as $m \leq (l+1)(l+2) - (m+1)^2$ when $(l, m) \in \Lambda$, we deduce that there exists a constant $C > 0$ such that

$$\begin{aligned} \forall (l, m) \in \Lambda, \quad ((l+1)(l+2) - m^2)^{\frac{s}{2}} \left| \widehat{(\partial_{x_j} u)}_l^m \right| &\leq C \left(\frac{1}{4} + (l+1)(l+2) - (m+1)^2 \right)^{\frac{s+1}{2}} \left| \hat{u}_{l+1}^{m+1} \right| \\ &\quad + C \left(\frac{1}{4} + (l+1)(l+2) - (m-1)^2 \right)^{\frac{s+1}{2}} \left| \hat{u}_{l+1}^{m-1} \right|. \end{aligned}$$

This implies the desired continuity. \square

Lemma 8. *For every $u \in T^1$, there holds*

$$\int_{\mathbb{D}} \omega(x) |\nabla u(x)|^2 dx = \frac{1}{2} \sum_{(l,m) \in \Lambda} (l(l+1) - m^2) |\hat{u}_l^m|^2. \quad (19)$$

Proof. The two quadratic functionals

$$u \mapsto \int_{\mathbb{D}} \omega(x) |\nabla u(x)|^2 dx, \quad u \mapsto \sum_{(l,m) \in \Lambda} (l(l+1) - m^2) |\hat{u}_l^m|^2$$

are continuous on \mathcal{T}^1 . The continuity of the first functional is a special case of Lemma 7 with $s = 0$ (noting that $\mathcal{U}^0 = L_\omega^2$), while the second one stems from the definition of the \mathcal{T}^1 norm. Therefore, it suffices to show that those functionals coincide on the dense subset of \mathcal{T}^1 consisting of the finite linear combinations of $\{T_l^m\}_{(l,m) \in \Lambda}$. If u is such a function, it is in particular twice differentiable, so we have by integration by parts

$$\int_{\mathbb{D}} \omega(x) |\nabla u(x)|^2 dx = \int_{\mathbb{D}} \frac{u(x) \overline{[-(\omega \operatorname{div} \omega \nabla) u](x)}}{\omega(x)} dx = (u, v)_\omega.$$

where $v = -(\omega \operatorname{div} \omega \nabla)u$. Using now Lemma 2, we have

$$v = \sum_{(l,m) \in \Lambda} (l(l+1) - m^2) T_l^m$$

and the result follows from the Parseva equality (18). \square

The following weighted Poincaré inequality holds. To the best of our knowledge, this result is not of the kind that one may encounter in standard literature about weighted Poincaré inequalities, such as [27, 34].

Theorem 1. *For all functions $u \in T^1$, there holds*

$$\int_{\mathbb{D}} \frac{|u(x) - u_\omega|^2}{\omega(x)} dx \leq \int_{\mathbb{D}} \omega(x) |\nabla u(x)|^2 dx, \quad (20)$$

where

$$u_\omega = \left(\int_{\mathbb{D}} \frac{1}{\omega(x)} dx \right)^{-1} \int_{\mathbb{D}} \frac{u(x)}{\omega(x)} dx.$$

Proof. It is easy to check that $u_\omega = \hat{u}_0^0 T_0^0$ since T_0^0 is constant on \mathbb{D} . We deduce the expression

$$\int_{\mathbb{D}} \frac{|u(x) - u_\omega|^2}{\omega(x)} dx = \frac{1}{2} \sum_{(l,m) \in \Lambda, l \neq 0} |\hat{u}_l^m|^2.$$

For $(l, m) \in \Lambda$ with $l \neq 0$, we have $1 \leq l(l+1) - m^2$ so

$$\int_{\mathbb{D}} \frac{|u(x) - u_\omega|^2}{\omega(x)} dx \leq \frac{1}{2} \sum_{(l,m) \in \Lambda} (l(l+1) - m^2) |\hat{u}_l^m|^2.$$

The right hand side is equal to $\int_{\mathbb{D}} \omega(x) |u(x)|^2 dx$ by Lemma 8, which proves the claim. \square

Lemma 9. *Let*

$$X := -\omega \operatorname{div} \omega \nabla + \frac{1}{4} \operatorname{Id}, \quad Y := -\operatorname{div} \omega \nabla \omega. \quad (21)$$

Then X is a positive self-adjoint, unbounded operator on $L_{\frac{1}{\omega}}^2$, with domain \mathcal{T}^2 . Similarly, Y is a positive self-adjoint, unbounded operator on L_ω^2 with domain \mathcal{U}^2 . They satisfy

$$X \left(\sum_{(l,m) \in \Lambda} \hat{u}_l^m T_l^m \right) = \sum_{(l,m) \in \Lambda} \left(\frac{1}{4} + l(l+1) - m^2 \right) \hat{u}_l^m T_l^m,$$

$$Y \left(\sum_{(l,m) \in \Lambda} \check{u}_l^m U_l^m \right) = \sum_{(l,m) \in \Lambda} ((l+1)(l+2) - m^2) \check{u}_l^m U_l^m.$$

For all $\alpha, s \in \mathbb{R}$, the operators $X^\alpha : \mathcal{T}^s \rightarrow \mathcal{T}^{s-2\alpha}$ and $Y^\alpha : \mathcal{U}^s \rightarrow \mathcal{U}^{s-2\alpha}$ are continuous and

$$\|u\|_{\mathcal{T}^s}^2 = \frac{1}{2} \left(X^{s/2} u, u \right)_{\frac{1}{\omega}}, \quad \|u\|_{\mathcal{U}^s}^2 = \frac{1}{2} \left(Y^{s/2} u, u \right)_\omega.$$

Proof. For finite linear combinations of T_l^m or U_l^m , the formulas for X and Y are direct consequences of Lemma 2. The formulas in the general case follow by density. The proofs of the self-adjointness of X and Y follow standard arguments and we omit them for conciseness. The formulas for the \mathcal{T}^s and \mathcal{U}^s norms follow directly from the definitions. \square

To conclude this section, we point out a characterization of the spaces \mathcal{T}^∞ and \mathcal{U}^∞ . This plays no role in the remainder of the article, but the result is worth mentioning.

Theorem 2. *There holds $\mathcal{T}^\infty = \mathcal{U}^\infty = C^\infty(\overline{\mathbb{D}})$.*

The proof is given Appendix A.

3 Parametrices for the integral operators

In this section, we define operators P_k and Q_k which will play the role of approximate inverses, or (weak) parametrices for the boundary integral operators V_k and W_k . They stand for the continuous versions of our proposed preconditioners, to be discretized in our numerical scheme. We start our discussion with the Laplace equation, i.e. $k = 0$.

3.1 Laplace layer potentials

We consider the following two sesquilinear forms $\mathcal{D}(\mathbb{D}) \times \mathcal{D}(\mathbb{D})$:

$$b_V(u, v) := \int_{\mathbb{D}} \int_{\mathbb{D}} \frac{u(x) \overline{v(y)} dx dy}{4\pi \|x - y\|},$$

$$b_W(u, v) := \int_{\mathbb{D}} \int_{\mathbb{D}} \frac{\mathbf{curl} u(x) \cdot \overline{\mathbf{curl} v(y)} dx dy}{4\pi \|x - y\|},$$

where $\mathbf{curl} u(x) := \begin{pmatrix} \partial_{x_2} u \\ -\partial_{x_1} u \end{pmatrix}$. They are well defined for smooth and compactly supported functions u and v on \mathbb{D} , and it is well-known that they extend uniquely to symmetric positive definite sesquilinear forms [40]

$$b_V : \tilde{H}^{-1/2}(\mathbb{D}) \times \tilde{H}^{-1/2}(\mathbb{D}) \rightarrow \mathbb{C}, \quad b_W : \tilde{H}^{1/2}(\mathbb{D}) \times \tilde{H}^{1/2}(\mathbb{D}) \rightarrow \mathbb{C}.$$

The spaces $H^s(\mathbb{D})$ and $\tilde{H}^s(\mathbb{D})$ are the Sobolev spaces of complex distributions defined e.g. in [30, chap. 3]. The associated operators $V : \tilde{H}^{-1/2}(\mathbb{D}) \rightarrow H^{1/2}(\mathbb{D})$ and $W : \tilde{H}^{1/2}(\mathbb{D}) \rightarrow H^{-1/2}(\mathbb{D})$ such that

$$b_V(u, v) = \langle Vu, \bar{v} \rangle, \quad b_W(u, v) = \langle Wu, \bar{v} \rangle,$$

are known as the weakly singular and hypersingular integral operators. Here again, the notation $\langle \cdot, \cdot \rangle$ stand for both the duality pairings between $H^{-1/2}(\mathbb{D})$ and $\tilde{H}^{1/2}(\mathbb{D})$ on the one hand, and between $\tilde{H}^{-1/2}(\mathbb{D})$ and $H^{1/2}(\mathbb{D})$ on the other hand.

The fact that b_V and b_W are positive definite allows us to consider them as the inner products of $\tilde{H}^{-1/2}(\mathbb{D})$ and $\tilde{H}^{1/2}(\mathbb{D})$, respectively. Furthermore, we endow $H^{1/2}(\mathbb{D})$ and $H^{-1/2}(\mathbb{D})$ with the dual norms:

$$\|u\|_{H^{1/2}(\mathbb{D})} := \sup_{v \in \tilde{H}^{-1/2}(\mathbb{D})} \frac{|\langle u, v \rangle|}{\|v\|_{\tilde{H}^{-1/2}(\mathbb{D})}} \quad \text{and} \quad \|u\|_{H^{-1/2}(\mathbb{D})} := \sup_{v \in \tilde{H}^{1/2}(\mathbb{D})} \frac{|\langle u, v \rangle|}{\|v\|_{\tilde{H}^{1/2}(\mathbb{D})}}.$$

For $s = 1/2$, this is equivalent to the norm defined via the Sobolev-Slobodeckij semi-norm, see [30, Thm 3.30].

The spaces \mathcal{T}^s and \mathcal{U}^s provide a good framework to analyze V and W . The main reason is the following result:

Proposition 2 (See [24, 36]). *For any $(l, m) \in \Lambda$, one has*

$$V\left(\frac{T_l^m}{\omega}\right) = \frac{T_l^m}{2\lambda_l^m} \quad \text{and} \quad W(\omega U_l^m) = \frac{\lambda_{l+1}^m}{2} U_l^m$$

where

$$\lambda_l^m = 2 \frac{\Gamma\left(\frac{l+m+2}{2}\right) \Gamma\left(\frac{l-m+2}{2}\right)}{\Gamma\left(\frac{l+m+1}{2}\right) \Gamma\left(\frac{l-m+1}{2}\right)}$$

and $\Gamma(t) = \int_0^{+\infty} s^{t-1} e^{-s} ds$ is the Gamma function.

The following estimate shows that $(\lambda_l^m)^2$ and the symbols of the weighted Laplacians (see Lemma 2), are equivalent:

Lemma 10. *One has the inequalities*

$$1 \leq \frac{(\lambda_l^m)^2}{\frac{1}{4} + l(l+1) - m^2} \leq \sqrt{3}, \quad l \in \mathbb{N}, \quad -l \leq m \leq l, \quad (22)$$

$$1 \leq \frac{(\lambda_l^m)^2}{l(l+1) - m^2} \leq \sqrt{3}, \quad l \in \mathbb{N}^*, \quad -l \leq m \leq l. \quad (23)$$

Proof. We start with the following improved version of Gautschi's inequality [28]:

$$\forall (x, s) \in \mathbb{R}_+^* \times (0, 1), \quad \left(x + \frac{s}{2}\right)^{1-s} \leq \frac{\Gamma(x+1)}{\Gamma(x+s)} \leq \left(x - \frac{1}{2} + \sqrt{s + \frac{1}{4}}\right)^{1-s}.$$

We apply this inequality for $s = \frac{1}{2}$, and notice that it remains true when $x = 0$. We may therefore take $x = \frac{l \pm m}{2}$ to obtain

$$\left(l + m + \frac{1}{2}\right) \left(l - m + \frac{1}{2}\right) \leq (\lambda_l^m)^2 \leq \left(l - m + \sqrt{3} - 1\right) \left(l + m + \sqrt{3} - 1\right).$$

Remarking that

$$\left(l + m + \frac{1}{2}\right) \left(l - m + \frac{1}{2}\right) = l(l+1) - m^2 + \frac{1}{4}$$

yields the left-hand side of the inequalities (22) and *a fortiori* (23).

For the right-hand side inequalities, we observe that for $l \geq 2$ and $-l \leq m \leq l$, one has

$$\begin{aligned} (l + \sqrt{3} - 1)^2 - m^2 &= l(l+1) - m^2 + (2\sqrt{3} - 3)l + 4 - 2\sqrt{3} \\ &\leq l(l+1) - m^2 + (2\sqrt{3} - 3)l + (4 - 2\sqrt{3})\frac{l}{2} \\ &\leq \sqrt{3}(l(l+1) - m^2) \end{aligned}$$

using that $l(l+1) - m^2 \geq l$. This establishes the right hand side inequality of (23) for $l \geq 2$, and one can check that the same inequality also holds for $l = 1$. This also implies *a fortiori* the right hand side inequality of (22) for $l \neq 0$, and again, one can check that it remains valid for $l = 0$. \square

Lemma 11. *There holds*

$$\tilde{H}^{-1/2}(\mathbb{D}) = (\mathcal{T}^{1/2})', \quad \tilde{H}^{1/2}(\mathbb{D}) = (\mathcal{U}^{-1/2})' \quad (24)$$

with the following norm equivalences:

$$\forall u \in (\mathcal{T}^{1/2})', \quad 3^{-1/4} \|u\|_{(\mathcal{T}^{1/2})'} \leq \sqrt{2} \|u\|_{\tilde{H}^{-1/2}(\mathbb{D})} \leq \|u\|_{(\mathcal{T}^{1/2})'}, \quad (25)$$

$$\forall u \in \mathcal{U}^{1/2}, \quad 3^{-1/4} \|u\|_{\mathcal{U}^{1/2}} \leq \sqrt{2} \|\omega u\|_{\tilde{H}^{1/2}(\mathbb{D})} \leq \|u\|_{\mathcal{U}^{1/2}}. \quad (26)$$

Proof. Consider $L \in \mathbb{N}$ and a function u of the form

$$u = \sum_{(l,m) \in \Lambda} \hat{u}_l^m T_l^m, \quad (27)$$

where $\hat{u}_l^m = 0$ for $l \geq L$. Putting $v = \frac{u}{\omega}$, we have, from Proposition 2:

$$Vv = \sum_{(l,m) \in \Lambda} \frac{\hat{u}_l^m}{2\lambda_l^m} T_l^m$$

hence $Vv \in C^\infty(\bar{\mathbb{D}})$. It follows that $v \in \tilde{H}^{-1/2}(\mathbb{D})$ and

$$\|v\|_{\tilde{H}^{-1/2}}^2 = \int_{\mathbb{D}} (Vv)(x) \frac{\overline{u(x)}}{\omega(x)} dx = \sum_{(l,m) \in \Lambda} \frac{|\hat{u}_l^m|^2}{2\lambda_l^m},$$

by the orthogonality properties of the T_l^m seen in the previous section. In view of the estimate (22), this implies

$$\frac{1}{2\sqrt{3}} \|u\|_{\mathcal{T}^{-1/2}}^2 \leq \left\| \frac{1}{\omega} u \right\|_{\tilde{H}^{-1/2}(\mathbb{D})}^2 \leq \frac{1}{2} \|u\|_{\mathcal{T}^{-1/2}}^2. \quad (28)$$

Finally, by the density of finite linear combinations of the form (27) in $\mathcal{T}^{-1/2}$, it follows that $\frac{1}{\omega} \mathcal{T}^{-1/2} = \tilde{H}^{-1/2}(\mathbb{D})$ with the norm equivalence (28) holding for all $u \in \mathcal{T}^{-1/2}$, where $\frac{1}{\omega}$ is understood as in Lemma 6. Since $\frac{1}{\omega} \mathcal{T}^{-1/2} = (\mathcal{T}^{1/2})'$, this proves the first norm equivalence (25). The proof of the second one is similar. \square

Corollary 1. *There holds*

$$H^{1/2}(\mathbb{D}) = \mathcal{T}^{1/2}, \quad H^{-1/2}(\mathbb{D}) = \mathcal{U}^{1/2}$$

with the following norm equivalences:

$$\forall u \in \mathcal{T}^{1/2}, \quad \|u\|_{\mathcal{T}^{1/2}} \leq \frac{1}{\sqrt{2}} \|u\|_{H^{1/2}} \leq 3^{\frac{1}{4}} \|u\|_{\mathcal{T}^{1/2}}, \quad (29)$$

$$\forall u \in \mathcal{U}^{-1/2}, \quad \|u\|_{\mathcal{U}^{-1/2}} \leq \frac{1}{\sqrt{2}} \|u\|_{H^{-1/2}} \leq 3^{\frac{1}{4}} \|u\|_{\mathcal{U}^{-1/2}}, \quad (30)$$

We can now state the main result of this article. Recall the definitions of the operators X and Y in Eq. (21).

Theorem 3. *The operator $P = \frac{1}{\omega} X^{\frac{1}{2}}$ maps $H^{1/2}(\mathbb{D})$ to $\tilde{H}^{-1/2}(\mathbb{D})$ bijectively and for all $u \in \tilde{H}^{-1/2}(\mathbb{D})$, there holds*

$$\frac{1}{2} \|u\|_{H^{1/2}(\mathbb{D})}^2 \leq \langle Pu, \bar{u} \rangle \leq \frac{\sqrt{3}}{2} \|u\|_{H^{1/2}(\mathbb{D})}^2 .$$

The operator $Q = \omega Y^{-1/2}$ maps $H^{-1/2}(\mathbb{D})$ to $\tilde{H}^{1/2}(\mathbb{D})$ bijectively and for all $u \in H^{-1/2}(\mathbb{D})$, there holds

$$\frac{1}{2} \|u\|_{H^{-1/2}(\mathbb{D})}^2 \leq \langle Qu, \bar{u} \rangle \leq \frac{\sqrt{3}}{2} \|u\|_{H^{-1/2}(\mathbb{D})}^2 .$$

Proof. By Lemma 9, we have, for all $u \in \mathcal{T}^{1/2}$, $\|u\|_{\mathcal{T}^{1/2}}^2 = \left(\sqrt{X}u, u \right)_{\frac{1}{\omega}} = \langle Pu, \bar{u} \rangle$. The result follows by applying the second norm equivalence of Lemma 11. The proof for the second claim is similar. \square

The previous result paves the way for a preconditioning strategy to solve the integral equations (1), that we present in Section 4.

3.2 Helmholtz layer potentials

We now seek corrections of the weighted Laplacians $-(\omega \operatorname{div} \omega \nabla)$ and $-(\operatorname{div} \omega \nabla \omega)$ in order to capture the behavior associated to non-zero wavenumbers. Let us first state a surprising commutation:

Theorem 4. *For any function $u \in C^\infty(\bar{\mathbb{D}})$, there holds*

$$(-\omega \operatorname{div} \omega \nabla - k^2 \omega^2) V_{k,\omega} u = V_{k,\omega} (-\operatorname{div} \omega \nabla \omega - k^2 \omega^2) u ,$$

where $V_{k,\omega} = V_k \frac{1}{\omega}$ is the composition of the Helmholtz weakly-singular operator with the multiplication by $1/\omega$.

The proof is given in Appendix B. To generalize our method for $k \neq 0$, we propose to propose the operators

$$P_k = \frac{1}{\omega} (-\omega \operatorname{div} \omega \nabla - k^2 \omega^2)^{\frac{1}{2}} , \quad Q_k = \omega (-\operatorname{div} \omega \nabla \omega - k^2 \omega^2)^{-\frac{1}{2}} , \quad (31)$$

to play the role of parametrices for V_k and W_k , respectively. The insights that motivate this choice are the following:

- Taking $\omega \equiv 1$ and ignoring the singularity of the screen \mathbb{D} , the formula for P_k leads back to pseudo-differential approximations of the Dirichlet-to-Neumann (DtN) map which was successfully used for preconditioning purposes, see [4, 5]. In the case of a flat screen, the DtN is simply a constant times the inverse of V_k , so the definition of P_k can be thought of as a generalization of this DtN approximation in the presence of an edge singularity.
- Using compact perturbation arguments, one can show that P_k and Q_k have the right mapping properties, i.e. $P_k : H^{1/2}(\mathbb{D}) \rightarrow \tilde{H}^{-1/2}(\mathbb{D})$, and $Q_k : H^{-1/2} \rightarrow \tilde{H}^{1/2}(\mathbb{D})$, are continuous, and continuously invertible for all but a countable set of values $k \in \mathbb{R}^+$.

- The above commutation implies that ωP_k and $V_{k,\omega}$ can be diagonalized in a common basis of eigenfunctions (one can check that the eigenfunctions of P_k turn out to be oblate spheroidal wave functions [15]). Hence, the product $V_k P_k = V_{k,\omega}(\omega P_k)$ is diagonal in this basis, while *a priori* $V_k P_0$ is not. This hints at the fact that $-k^2\omega^2$ is the “correct” k -dependent perturbation to add under the square-root. Perhaps, some fine eigenvalue estimates could show that $V_k P_k$ is close to a multiple of identity, although the required asymptotic results do not seem at reach for now.
- There is a striking analogy with the two-dimensional case [3], where a pseudo-differential analysis shows that, for the 2D analogs of P_k and Q_k , $-k^2\omega^2$ is the order zero perturbation of that leads to the most smoothing remainders R and R' in the formulas $V_k P_k = I_d/2 + R$, $W_k Q_k = I_d/2 + R'$, as measured in a suitable pseudo-differential scale [6].
- Eventually, the numerical evidence presented in Section 5 is very convincing.

Yet, a more rigorous justification of those choices remains to be proposed.

4 Galerkin discretization and preconditioners

4.1 Variational problems

Given some data $f \in H^{-1/2}(\mathbb{D})$ and $g \in H^{1/2}(\mathbb{D})$ and a wavenumber $k \geq 0$, we consider the following two variational formulations of the integral equations (1):

$$\text{Find } \lambda \in \tilde{H}^{-1/2}(\mathbb{D}) \text{ such that } \forall \lambda' \in \tilde{H}^{-1/2}(\mathbb{D}), \quad \langle V_k \lambda, \lambda' \rangle = \langle f, \lambda' \rangle, \quad (32)$$

$$\text{Find } \mu \in \tilde{H}^{1/2}(\mathbb{D}) \text{ such that } \forall \mu' \in \tilde{H}^{1/2}(\mathbb{D}), \quad \langle W_k \mu, \mu' \rangle = \langle g, \mu' \rangle. \quad (33)$$

We introduce two sequences of subspaces $\mathcal{V}_N \subset \tilde{H}^{-1/2}(\mathbb{D})$ and $\mathcal{W}_N \subset \tilde{H}^{1/2}(\mathbb{D})$ for $N \in \mathbb{N}$, and define the approximate solutions $(\lambda_N)_{N \in \mathbb{N}}$ and $(\mu_N)_{N \in \mathbb{N}}$ to the variational problems (32) and (33) by the Galerkin method as

$$\lambda_N \in \mathcal{V}_N, \quad \forall \lambda' \in \mathcal{V}_N, \quad \langle V_k \lambda_N, \lambda' \rangle = \langle f, \lambda' \rangle, \quad (34)$$

$$\mu_N \in \mathcal{W}_N, \quad \forall \mu' \in \mathcal{W}_N, \quad \langle W_k \mu_N, \mu' \rangle = \langle g, \mu' \rangle. \quad (35)$$

We introduce two basis $\{\varphi_i^N\}_{1 \leq i \leq \dim \mathcal{V}_N}$ and $\{\psi_i^N\}_{1 \leq i \leq \dim \mathcal{W}_N}$ of \mathcal{V}_N and \mathcal{W}_N . The vectors Λ_N and U_N of coefficients of λ_N and μ_N in those respective basis are obtained by solving the systems

$$\mathbf{V}_k \Lambda_N = F_N, \quad (36)$$

$$\mathbf{W}_k U_N = G_N, \quad (37)$$

where \mathbf{V}_k and \mathbf{W}_k are the Galerkin matrices defined by

$$(\mathbf{V}_k)_{ij} = \langle V_k \varphi_i^N, \overline{\varphi_j^N} \rangle, \quad 1 \leq i, j \leq \dim \mathcal{V}_N, \quad (38)$$

$$(\mathbf{W}_k)_{ij} = \langle W_k \psi_i^N, \overline{\psi_j^N} \rangle, \quad 1 \leq i, j \leq \dim \mathcal{W}_N, \quad (39)$$

with the column vectors

$$(F_N)_i = \langle f, \overline{\varphi_i^N} \rangle, \quad 1 \leq i \leq \dim \mathcal{V}_N, \quad (G_N)_i = \langle g, \overline{\psi_i^N} \rangle, \quad 1 \leq i \leq \dim \mathcal{W}_N. \quad (40)$$

The purpose of this section is to specify the choices of spaces \mathcal{V}_N and \mathcal{W}_N and their basis, and to define preconditioners $\widehat{\mathbf{P}}_k$ and $\widehat{\mathbf{Q}}_k$ for the dense linear systems (36) and (37) respectively. Furthermore, we estimate the condition number of the preconditioned linear system $\widehat{\mathbf{P}}_k \mathbf{V}_k$ in the special case of quasi-uniform meshes and $k = 0$.

In the remainder of this paper, the subscript k is omitted when $k = 0$, i.e. we write $V, W, \widehat{\mathbf{P}}, \widehat{\mathbf{Q}}$ instead of $V_0, W_0, \widehat{\mathbf{P}}_0, \widehat{\mathbf{Q}}_0$ and so on.

4.2 Abstract condition number estimate

In this paragraph, we fix $N \in \mathbb{N}$ and consider a subspace $\mathcal{X}_N \subset H^{1/2}(\mathbb{D})$ with $\dim \mathcal{X}_N = \dim \mathcal{V}_N$. Let $p : \mathcal{X}_N \times \mathcal{X}_N \rightarrow \mathbb{C}$ be a sesquilinear form that is continuous and coercive in the $\mathcal{T}^{1/2}$ norm on \mathcal{X}_N , i.e. such that

$$\exists c_p(N), C_p(N) > 0, \quad \forall \theta \in \mathcal{X}_N, \quad c_p(N) \|\theta\|_{\mathcal{T}^{1/2}}^2 \leq p(\theta, \theta) \leq C_p(N) \|\theta\|_{\mathcal{T}^{1/2}}^2. \quad (41)$$

We introduce a basis $\{\theta_i^N\}_{1 \leq i \leq \dim \mathcal{X}_N}$ of \mathcal{X}_N and define the square $N \times N$ matrices

$$\mathbf{P} := (p(\theta_i^N, \theta_j^N))_{1 \leq i, j \leq N}, \quad \mathbf{D} := \left(\left\langle \varphi_i^N, \overline{\theta_j^N} \right\rangle \right)_{1 \leq i, j \leq N}. \quad (42)$$

With those definitions, let

$$\widehat{\mathbf{P}} := \mathbf{D}^{-1} \mathbf{P} \mathbf{D}^{-T}. \quad (43)$$

To analyze the preconditioning matrix $\widehat{\mathbf{P}}$, the key quantity, besides the constants $c_p(N)$ and $C_p(N)$ appearing in (41) is the following inf-sup stability constant:

$$\sigma(\mathcal{V}_N, \mathcal{X}_N) := \inf_{\varphi \in \mathcal{V}_N} \sup_{\theta \in \mathcal{X}_N} \frac{|\langle \varphi, \overline{\theta} \rangle|}{\|\varphi\|_{\widetilde{H}^{-1/2}} \|\theta\|_{H^{1/2}}}. \quad (44)$$

Indeed, we have the following result:

Theorem 5. *There holds*

$$\kappa(\widehat{\mathbf{P}} \mathbf{V}) \leq \frac{\sqrt{3}}{\sigma(\mathcal{V}_N, \mathcal{X}_N)^2} \frac{C_p(N)}{c_p(N)}$$

where $\kappa(\mathbf{M})$ is the condition number of the matrix \mathbf{M} , defined as the ratio of the largest to the smallest singular value of \mathbf{M} .

Proof. By Theorem 2.1 from [22], we have

$$\kappa(\widehat{\mathbf{P}} \mathbf{V}) \leq \frac{\|a\| \|p\| \|d\|^2}{c_A c_P c_D^2} \quad (45)$$

where $a : \mathcal{V}_N \times \mathcal{V}_N \rightarrow \mathbb{C}$ and $d : \mathcal{V}_N \times \mathcal{W}_N \rightarrow \mathbb{C}$ are the sesquilinear forms defined by

$$\forall \varphi \in \mathcal{V}_N, \quad a(\varphi, \varphi) = \|\varphi\|_{\widetilde{H}^{-1/2}}^2, \quad d(\varphi, \theta) := \langle \varphi, \overline{\theta} \rangle,$$

and the constants appearing in the estimate are chosen so that

$$c_A \|u\|_{\widetilde{H}^{-1/2}}^2 \leq a(u, u) \leq \|a\| \|u\|_{\widetilde{H}^{-1/2}}^2$$

$$|d(u, v)| \leq \|d\| \|u\|_{\tilde{H}^{-1/2}} \|v\|_{\mathcal{T}^{1/2}}$$

$$c_P \|u\|_{\mathcal{T}^{1/2}}^2 \leq p(u, u) \leq \|p\| \|u\|_{\mathcal{T}^{1/2}}^2 .$$

Since $a(u, u) = \|u\|_{\tilde{H}^{-1/2}}^2$, we can take $c_A = \|a\| = 1$. Similarly, in view of (41), we can use $c_P = c_p(N)$ and we have $\|p\| \leq C_p(N)$. By the norm equivalence stated in Corollary 1,

$$|d(\varphi, \theta)| \leq \|\varphi\|_{\tilde{H}^{-1/2}} \|\theta\|_{H^{1/2}} \leq 3^{1/4} \sqrt{2} \|\varphi\|_{\tilde{H}^{-1/2}} \|\theta\|_{\mathcal{T}^{1/2}} ,$$

hence $\|d\| \leq 3^{1/4} \sqrt{2}$. Furthermore, combining the same norm equivalence with Eq. (44), we get

$$\forall \varphi_N \in \mathcal{V}_N, \quad \sup_{\theta \in \mathcal{X}_N} \frac{|d(\varphi_N, \theta)|}{\|\theta\|_{\mathcal{T}^{1/2}}} \geq \frac{\sqrt{2}}{3^{1/4}} \sigma(\mathcal{V}_N, \mathcal{X}_N) \|\varphi_N\|_{\tilde{H}^{-1/2}} .$$

Hence we may take $c_D = \frac{\sqrt{2}}{3^{1/4}} \sigma(\mathcal{V}_N, \mathcal{W}_N)$. It remains to inject those values in the estimate (45) to conclude the proof. \square

To apply this result concretely, we are going to

- (i) specify spaces $\mathcal{V}_N, \mathcal{X}_N$ and estimate the constant $\sigma(\mathcal{V}_N, \mathcal{X}_N)$ of Eq. (44),
- (ii) propose an explicit sesquilinear form p which satisfies (41), and estimate the ratio $C_p(N)/c_p(N)$.

4.3 Stable discretization with uniform meshes

We describe a stable discretization involving spaces of continuous piecewise linear functions, both for the operator and the preconditioner, over a sequence of globally quasi-uniform and shape-regular triangular meshes. We prove that this family of subspaces provides a uniformly stable discretization, see Lemma 15. The extension of the theory to more general discretizations is left for future work.

Let us consider a sequence of polygons $(P_N)_{N \in \mathbb{N}}$, with all of their vertices in $\partial \mathbb{D}$. We denote by h_N the maximal distance between two consecutive vertices of \mathbb{D}_N and assume that

$$\lim_{N \rightarrow \infty} h_N = 0 .$$

This way, the polygons P_N asymptotically cover \mathbb{D} . Let \mathcal{T}_N be a triangulation of P_N , with the property that every vertex in the boundary of \mathcal{T}_N is a vertex of P_N . For a triangle $\tau \in \mathcal{T}_N$, we denote by h_τ its diameter and by Δ_τ its area. We make the following assumptions:

$$\forall N \in \mathbb{N}, \forall \tau \in \mathcal{T}_N, \quad c \leq \frac{h_\tau}{h_N} \leq C \quad (\text{global quasi-uniformity}), \quad (46)$$

$$\forall N \in \mathbb{N}, \forall \tau \in \mathcal{T}_N, \quad \frac{\Delta_\tau}{h_\tau^2} \geq c \quad (\text{uniform shape-regularity}). \quad (47)$$

Here and in what follows, $c > 0$ and $C > 0$ denote generic constants that are independent of N and of the choice of a specific triangle $\tau \in \mathcal{T}_N$. For each $N \in \mathbb{N}$, we choose \mathcal{V}_N as the finite-dimensional subspace of $\tilde{H}^{-1/2}(\mathbb{D})$ consisting of all functions $\varphi : \mathbb{D} \rightarrow \mathbb{C}$ such that

- $\varphi|_\tau$ is an affine function for each $\tau \in \mathcal{T}_N$
- φ is continuous on $\overline{P_N}$.

- φ vanishes in $\overline{\mathbb{D}} \setminus \overline{P_N}$.

To define $\mathcal{X}_N \subset \mathcal{T}^{1/2}$, we proceed as follows. If a triangle $\tau \in \mathcal{T}_N$ has two vertices A and B in $\partial\mathbb{D}$, we define U_τ as the region of \mathbb{D} enclosed on the one hand by the (smallest) arc of $\partial\mathbb{D}$ linking A to B , and on the other hand by the straight line segment $[A, B]$. For each $\tau \in \mathcal{T}_N$, we then define a corresponding open set $K_\tau \subset \mathbb{D}$ by

$$\overline{K_\tau} = \begin{cases} \overline{\tau} & \text{if } \tau \text{ has at most one vertex in } \partial\mathbb{D}, \\ \overline{\tau} \cup \overline{U_\tau} & \text{otherwise.} \end{cases}$$

Hence, the domains K_τ are either triangles, or triangles with one side replaced by an arc of $\partial\mathbb{D}$. The set $\{K_\tau\}_{\tau \in \mathcal{T}_N}$ is a partition of \mathbb{D} , in the sense that

$$\bigcup_{\tau \in \mathcal{T}_N} \overline{K_\tau} = \overline{\mathbb{D}}.$$

With these definitions, let

$$\mathcal{X}_N := \{ \theta \in C^0(\overline{\mathbb{D}}) \mid \theta|_{K_\tau} \text{ is affine for each } \tau \in \mathcal{T}_N \}.$$

We have $\mathcal{X}_N \subset \mathcal{T}^{1/2} = H^{1/2}(\mathbb{D})$ (while this is not true of \mathcal{V}_N).

For every element $\varphi \in \mathcal{V}_N$, we denote by $E_N\varphi$ the unique element of \mathcal{X}_N which coincides with φ on P_N .

Lemma 12. *One has the estimate*

$$\forall N \in \mathbb{N}, \forall \varphi \in \mathcal{V}_N, \quad \|\varphi - E_N\varphi\|_{L^2(\mathbb{D})}^2 \leq Ch_N \|\varphi\|_{L^2(\mathbb{D})}^2$$

Proof. We start by writing

$$\|\varphi - E_N\varphi\|_{L^2(\mathbb{D})}^2 = \sum_{e \in \partial\mathcal{T}_N} \int_{U_e} |\varphi|_{\tau(e)}(x)|^2 dx.$$

Fix an edge $e \in \partial\mathcal{T}_N$, and let $\tau(e)$ be the triangle of \mathcal{T}_N incident to e . Then $\varphi|_{\tau(e)}$ can be written in the form

$$\varphi|_{\tau(e)}(x) = \langle A, x - C \rangle + \varphi(C)$$

where C is the vertex of τ not in e and the vector A satisfies

$$\|A\|_2 \leq Ch_\tau \frac{\|\varphi|_{\tau(e)}\|_\infty}{\Delta_{\tau(e)}} \leq C \frac{\|\varphi|_{\tau(e)}\|_\infty}{h_{\tau(e)}},$$

where we used the shape-regularity assumption (47). Furthermore, one has the crude estimate $\|x - C\|_2 \leq 2h_{\tau(e)}$ for $x \in U_e := K_{\tau(e)} \setminus \overline{\tau(e)}$. Hence, we conclude

$$\|\varphi - E_N\varphi\|_{L^2(\mathbb{D})}^2 \leq C \sum_{e \in \partial\mathcal{T}_N} \|\varphi|_{\tau(e)}\|_\infty^2 |U_e|. \quad (48)$$

We have $|U_e| \leq Ch_{\tau(e)}^3$, and, using a local inverse inequality,

$$\|\varphi|_{\tau(e)}\|_\infty^2 \leq Ch_{\tau(e)}^{-2} \int_{\tau(e)} |\varphi(x)|^2 dx.$$

Injecting those estimates in Eq. (48) and using the global quasi-uniformity assumption (47) gives the result. \square

We have the following approximation property in \mathcal{X}_N .

Lemma 13. *For each $u \in H^{1/2}(\mathbb{D})$ and for each $N \in \mathbb{N}$, there exists $\theta \in \mathcal{X}_N$ satisfying*

$$\|u - \theta\|_{L^2(\mathbb{D})} + \sqrt{h_N} \|u - \theta\|_{H^{1/2}(\mathbb{D})} \leq C \sqrt{h_N} \|u\|_{H^{1/2}(\mathbb{D})} .$$

This result is standard for polygonal meshes, and the extension to our context, where the mesh includes some rounded triangles at the edge, presents no difficulty, so we omit the proof. The same goes for the next lemma:

Lemma 14. *For all $\varphi \in \mathcal{V}_N$, one has*

$$\sqrt{h_N} \|\varphi\|_{L^2(\mathbb{D})} \leq C \|\varphi\|_{\tilde{H}^{-1/2}(\mathbb{D})} ,$$

and for all $\theta \in \mathcal{X}_N$, one has

$$\sqrt{h_N} \|\theta\|_{H^{1/2}(\mathbb{D})} \leq C \|\theta\|_{L^2(\mathbb{D})} .$$

By a classical argument, a global inverse inequality in combination with an approximation property ensures stability of the L^2 projection operator in the energy norm (see e.g. the proof of [9, Lemma 1]). Hence

Corollary 2. *Let $\pi_N : L^2(\mathbb{D}) \rightarrow \mathcal{X}_N$ be the L^2 projection onto \mathcal{X}_N . Then there exists a constant $C_\pi > 0$ such that*

$$\forall u \in H^{1/2}(\mathbb{D}), \quad \|\pi_N u\|_{H^{1/2}(\mathbb{D})} \leq C_\pi \|u\|_{H^{1/2}(\mathbb{D})} .$$

Lemma 15. *There exists a constant $\sigma_0 > 0$ and an index $N_0 \in \mathbb{N}$ such that for all $N \geq N_0$,*

$$\sigma(\mathcal{V}_N, \mathcal{X}_N) \geq \sigma_0 ,$$

where $\sigma(\mathcal{V}_N, \mathcal{X}_N)$ is the inf-sup constant defined in Eq. (44).

Proof. Let $\varphi \in \mathcal{V}_N$ and let $\theta = \pi_N V\varphi$. One has $\|\theta\|_{H^{1/2}} \leq C_\pi \|\varphi\|_{\tilde{H}^{-1/2}(\mathbb{D})}$ by Corollary 2. Moreover, one can write

$$\begin{aligned} \langle \varphi, \bar{\theta} \rangle &= \langle v_j, \overline{V\varphi} \rangle + \langle v_j, (I_d - \pi_N) \overline{V\varphi} \rangle \\ &= \|\varphi\|_{\tilde{H}^{-1/2}}^2 + \langle (I_d - E_N)\varphi, (I_d - \pi_N) \overline{V\varphi} \rangle , \end{aligned}$$

using the orthogonality properties of π_N . Hence, using Lemmas 12, 13 and 14, we find

$$|\langle \varphi, \bar{\theta} \rangle| \geq \|\varphi\|_{\tilde{H}^{-1/2}}^2 - \sqrt{h_N} \|\varphi\|_{\tilde{H}^{-1/2}} \|V\varphi\|_{H^{1/2}} = (1 - \sqrt{h_N}) \|\varphi\|_{\tilde{H}^{-1/2}}^2 .$$

Therefore, we have established

$$\frac{|\langle \varphi, \bar{\theta} \rangle|}{\|\varphi\|_{\tilde{H}^{-1/2}} \|\theta\|_{H^{1/2}}} \geq \frac{1 - \sqrt{h_N}}{C_\pi}$$

which proves the lemma since $h_N \rightarrow 0$ when $N \rightarrow \infty$. □

4.4 Sesquilinear form p

We define a discrete weighted Laplacian $X_N : \mathcal{X}_N \rightarrow \mathcal{X}_N$ in the following way: for $\theta \in \mathcal{X}_N$, $X_N\theta$ is the element of \mathcal{X}_N satisfying

$$\forall \theta' \in \mathcal{X}_N, \quad (X_N\theta, \theta')_{\frac{1}{\omega}} = (X\theta, \theta')_{\frac{1}{\omega}} = \frac{1}{4} \int_{\mathbb{D}} \frac{\theta(x)\overline{\theta'(x)}}{\omega(x)} dx + \int_{\mathbb{D}} \omega(x) \nabla\theta(x) \cdot \overline{\nabla\theta'(x)} dx.$$

This operator is self-adjoint and positive definite with respect to the scalar product $(\cdot, \cdot)_{\frac{1}{\omega}}$. For $s \in [0, 1]$, let

$$\|\theta\|_{N,s}^2 := (X_N^s\theta, \theta)_{\frac{1}{\omega}}$$

which plays the role of a discrete \mathcal{T}^s norm on \mathcal{X}_N . Let \mathcal{X}_N^s denote the finite dimensional Hilbert space defined by $(\mathcal{X}_N, \|\cdot\|_{N,s})$. Reasoning with eigenfunctions of X_N in \mathcal{X}_N , it is easy to check that $(\mathcal{X}_N^s)_{0 \leq s \leq 1}$ is an interpolation scale. The identity operator is continuous (with norm 1) from \mathcal{X}_N^s to \mathcal{T}^s for $s = 0$ and $s = 1$. By interpolation, we deduce the following estimate:

Lemma 16. *For all $s \in [0, 1]$, there holds*

$$\forall \theta \in \mathcal{X}_N, \quad \|\theta\|_{\mathcal{T}^s} \leq \|\theta\|_{N,s}.$$

On the other hand, the fact that the \mathcal{T}^s norm controls the $\|\cdot\|_{N,s}$ norm can be shown by exhibiting a stable projection operator, as we show below. Here again, the argument is inspired by the proof of [9, Lemma 1]:

Lemma 17. *For each $N \in \mathbb{N}$, let $\Pi_N : L_{\frac{1}{\omega}}^2 \rightarrow \mathcal{X}_N$ be a linear operator satisfying the following assumptions:*

- (i) $\exists C_0 > 0 : \forall N \in \mathbb{N}, \forall u \in \mathcal{T}^0, \quad \|\Pi_N u\|_{\mathcal{T}^0} \leq C_0 \|u\|_{\mathcal{T}^0},$
- (ii) $\exists C_1 > 0 : \forall N \in \mathbb{N}, \forall u \in \mathcal{T}^1, \quad \|\Pi_N u\|_{\mathcal{T}^1} \leq C_1 \|u\|_{\mathcal{T}^1},$
- (iii) $\forall \theta \in \mathcal{X}_N, \Pi_N \theta = \theta.$

Then, for all $s \in [0, 1]$, there holds

$$\forall \theta \in \mathcal{X}_N, \quad \|\theta\|_{N,s} \leq C_0^{1-s} C_1^s \|\theta\|_{\mathcal{T}^s}.$$

Proof. By (i) and (ii), it follows by interpolation that for all $s \in [0, 1]$:

$$\forall u \in \mathcal{T}^s, \quad \|\Pi_N u\|_{N,s} \leq C_0^{1-s} C_1^s \|u\|_{\mathcal{T}^s}$$

The conclusion is immediate by restriction to \mathcal{X}_N , using (iii). \square

It turns out that such an operator Π_N is provided by the $L_{\frac{1}{\omega}}^2$ -orthogonal projection $\pi_{N,\omega}$ onto \mathcal{X}_N . Obviously, $\pi_{N,\omega}$ satisfies the properties (i) and (iii), while the \mathcal{T}^1 -stability (ii) is shown in [8, Theorem 1]. Hence, we have the following result:

Theorem 6. *Define the sesquilinear form p by*

$$p(\theta, \theta') := \left(X_N^{1/2} \theta, \theta' \right)_{\frac{1}{\omega}}. \quad (49)$$

Then p satisfies

$$\forall \theta \in \mathcal{X}_N \quad \|\theta\|_{\mathcal{T}^{1/2}}^2 \leq p(\theta, \theta) \leq C_{\pi} \|\theta\|_{\mathcal{T}^{1/2}}^2.$$

Gathering the previous results, we have thus established the existence of a uniform bound on the condition number of the preconditioned system $\widehat{\mathbf{P}}\mathbf{V}$, with $\widehat{\mathbf{P}}$ defined in Eq. (43) and p defined by Eq. (49).

Corollary 3. *There exist an index $N_0 > 0$ and a constant $\kappa_0 > 0$ such that for all $N \geq N_0$,*

$$\kappa(\widehat{\mathbf{P}}\mathbf{V}) \leq \kappa_0.$$

4.5 Computation of the preconditioner

For the basis $\{\varphi_i^N\}_{1 \leq i \leq \dim \mathcal{V}_N}$ of \mathcal{V}_N , we choose the classical nodal basis associated with the vertices of the triangulation \mathcal{T}_N . Moreover, we put

$$\theta_i^N := E_N \varphi_i^N, \quad 1 \leq i \leq \dim \mathcal{X}_N.$$

and this in turn provides a basis for \mathcal{X}_N . Notice that both basis consist of real-valued functions, hence the complex conjugation is irrelevant in what follows. With those definitions, the matrix \mathbf{D} is sparse and well-conditioned, so the evaluation of \mathbf{D}^{-1} is cheap (in fact, \mathbf{D} is nothing else than the standard mass matrix on the triangulation \mathcal{T}_N of the polygonal domain P_N). To evaluate the preconditioner $\widehat{\mathbf{P}} = \mathbf{D}^{-1}\mathbf{P}\mathbf{D}^{-T}$, the main task is therefore to compute \mathbf{P} .

To this aim, we first remark that the matrix \mathbf{M}_X of the linear operator $X_N : \mathcal{X}_N \rightarrow \mathcal{X}_N$ in the basis $\{\theta_i^N\}_{1 \leq i \leq \dim \mathcal{X}_N}$ is given by

$$\mathbf{M}_X = \mathbf{I}_{\frac{1}{\omega}}^{-1} \mathbf{X}_{\frac{1}{\omega}}$$

where $\mathbf{I}_{\frac{1}{\omega}}$ and $\mathbf{X}_{\frac{1}{\omega}}$ are the $(\dim \mathcal{X}_N) \times (\dim \mathcal{X}_N)$ weighted “mass” and “stiffness” matrices defined by

$$(\mathbf{I}_{\frac{1}{\omega}})_{ij} = \int_{\mathbb{D}} \frac{\theta_i^N(x) \theta_j^N(x)}{\omega(x)} dx, \quad (\mathbf{X}_{\frac{1}{\omega}})_{ij} := \frac{1}{4} \int_{\mathbb{D}} \frac{\theta_i^N(x) \theta_j^N(x)}{\omega(x)} dx + \int_{\mathbb{D}} \omega(x) \nabla \theta_i^N(x) \cdot \nabla \theta_j^N(x) dx,$$

for i, j in $\{1, \dots, \dim(\mathcal{X}_N)\}$. Those matrices can be computed using accurate quadrature rules for integrals of the form

$$\int_{K_\tau} \frac{f(x)}{\omega(x)} dx, \quad \tau \in \mathcal{T}_N.$$

We spare the reader with the technical details about the construction of such quadratures, and instead refer to our openly available implementation [7].

The matrix \mathbf{P} is equal to

$$\mathbf{P} = \mathbf{I}_{\frac{1}{\omega}} \sqrt{\mathbf{M}_X} = \mathbf{I}_{\frac{1}{\omega}} \sqrt{\mathbf{I}_{\frac{1}{\omega}}^{-1} \mathbf{X}_{\frac{1}{\omega}}} \quad (50)$$

To evaluate the matrix square root, we use the approach of [21]. This involves a formula of the form

$$\sqrt{\mathbf{M}_X} \approx \sum_{q=1}^Q a_q (I_d + b_q \mathbf{M}_X)^{-1} \mathbf{M}_X = \sum_{q=1}^Q a_q (\mathbf{I}_{\frac{1}{\omega}} + b_q \mathbf{X}_{\frac{1}{\omega}})^{-1} \mathbf{X}_{\frac{1}{\omega}}$$

for some carefully chosen coefficients a_q and b_q , with $b_q > 0$. It is shown in [21] that, under suitable hypotheses on \mathbf{M}_X , the error in Froebenius norm of this approximation converges exponentially fast to 0 with respect to Q . In the end, the approximation of \mathbf{P} is thus given by

$$\mathbf{P} \approx \mathbf{I}_{\frac{1}{\omega}} \sum_{q=1}^Q a_q (\mathbf{I}_{\frac{1}{\omega}} + b_q \mathbf{X}_{\frac{1}{\omega}})^{-1} \mathbf{X}_{\frac{1}{\omega}}. \quad (51)$$

In all of our tests, we take $Q = 5$. The matrix $\mathbf{I}_{\frac{1}{\omega}} + b_q \mathbf{X}_{\frac{1}{\omega}}$ is sparse and symmetric positive definite. Hence, the systems

$$(\mathbf{I}_{\frac{1}{\omega}} + b_q \mathbf{X}_{\frac{1}{\omega}})U = L$$

can be solved efficiently. Furthermore, the evaluation of the sum can be done in parallel. This allows for a cheap computation of the matrix-vector product $X \mapsto \mathbf{P}X$.

The previous subsections provide a complete description of our approach for preconditioning the Galerkin problem associated to the Laplace weakly-singular integral equation on uniform meshes. In the next sections, we indicate briefly how we tackle hypersingular equations and non-zero wavenumbers.

4.6 Extension to the hypersingular equation

Let us define

$$\mathcal{W}_N := \{\varphi \in \mathcal{V}_N \mid \varphi = 0 \text{ on } \partial\mathbb{D}_N\} \subset \tilde{H}^{1/2}(\mathbb{D}),$$

and let $\mathcal{Y}_N := E_N \mathcal{W}_N$. Let $\{\psi_i^N\}_{1 \leq i \leq \dim \mathcal{W}_N}$ be the nodal basis of \mathcal{W}_N and let $\{\nu_i^N\}_{1 \leq i \leq \dim \mathcal{Y}_N}$ be the basis of \mathcal{Y}_N defined by

$$\nu_i^N = E_N \psi_i^N, \quad 1 \leq i \leq \dim \mathcal{Y}_N.$$

Let $\tilde{\mathbf{D}}$ be the matrix of the duality pairing on $\mathcal{W}_N \times \mathcal{Y}_N$, that is

$$\tilde{\mathbf{D}}_{ij} := \langle \psi_i^N, \overline{\nu_j^N} \rangle, \quad 1 \leq i, j \leq \dim \mathcal{W}_N. \quad (52)$$

Consider a well-chosen sesquilinear form $q : \mathcal{Y}_N \times \mathcal{Y}_N$, with the concrete definition given below. We then define

$$\mathbf{Q}_{ij} := q(\nu_i^N, \nu_j^N), \quad 1 \leq i, j \leq \dim \mathcal{Y}_N.$$

We propose to use the matrix

$$\hat{\mathbf{Q}} := \tilde{\mathbf{D}}^{-1} \mathbf{Q} \tilde{\mathbf{D}}^{-T} \quad (53)$$

as a preconditioner for the Galerkin matrix \mathbf{W} of the hypersingular operator on \mathcal{W}_N .

For the sesquilinear form q , we consider again another discrete weighted Laplacian $Y_N : \mathcal{Y}_N \rightarrow \mathcal{Y}_N$ such that for each $\nu \in \mathcal{Y}_N$, $Y_N \nu$ is the element of \mathcal{Y}_N satisfying

$$\forall \nu' \in \mathcal{Y}_N, \quad (Y_N \nu, \nu')_{\omega} = (Y \nu, \nu')_{\omega} = \int_{\mathbb{D}} \frac{(\omega \nabla \omega \nu(x)) \cdot (\overline{\omega \nabla \omega \nu'(x)})}{\omega(x)} dx.$$

Since Y_N is positive definite in the scalar product $(\cdot, \cdot)_{\omega}$, we may define

$$q(\nu, \nu') := \left(Y_N^{-1/2} \nu, \nu' \right)_{\omega}, \quad \nu, \nu' \in \mathcal{Y}_N.$$

Notice again that the matrix \mathbf{M}_Y of the linear operator $Y_N : \mathcal{Y}_N \rightarrow \mathcal{Y}_N$ is given by

$$\mathbf{M}_Y = \mathbf{I}_{\omega}^{-1} \mathbf{Y}_{\omega},$$

where \mathbf{I}_{ω} and \mathbf{Y}_{ω} are the $(\dim \mathcal{Y}_N) \times (\dim \mathcal{Y}_N)$ weighted mass and stiffness matrices defined by

$$(\mathbf{I}_{\omega})_{ij} = \int_{\mathbb{D}} \omega(x) \nu_i^N(x) \overline{\nu_j^N(x)} dx, \quad (\mathbf{Y}_{\omega})_{ij} := \int_{\mathbb{D}} \frac{(\omega \nabla \omega \nu_i^N(x)) \cdot (\overline{\omega \nabla \omega \nu_j^N(x)})}{\omega(x)} dx,$$

for i, j in $\{1, \dots, \dim(Y_N)\}$. Hence, there holds

$$\mathbf{Q} = \mathbf{I}_\omega (\mathbf{I}_\omega^{-1} \mathbf{Y}_\omega)^{-1/2} = \mathbf{I}_\omega (\mathbf{I}_\omega^{-1} \mathbf{Y}_\omega)^{1/2} (\mathbf{I}_\omega^{-1} \mathbf{Y}_\omega)^{-1} = \mathbf{I}_\omega \sqrt{\mathbf{I}_\omega^{-1} \mathbf{Y}_\omega \mathbf{Y}_\omega^{-1} \mathbf{I}_\omega}. \quad (54)$$

For the efficient computation of the square root, the approach of the previous section also applies here, and leads to an approximation of the form

$$\mathbf{Q} \approx \mathbf{I}_\omega \sum_{q=1}^Q a_q (\mathbf{I}_\omega + b_q \mathbf{Y}_\omega)^{-1} \mathbf{I}_\omega. \quad (55)$$

4.7 Positive wavenumber

When $k > 0$, we proposed in subsection 3.2 to use the operators

$$P_k = \frac{1}{\omega} (-\omega \operatorname{div} \omega \nabla - k^2 \omega^2)^{\frac{1}{2}}, \quad Q_k = \omega (-\omega \operatorname{div} \omega \nabla - k^2 \omega^2)^{-\frac{1}{2}},$$

as parametrices for V_k and W_k , respectively. For the Galerkin discretization, we proceed by analogy with the two previous sections. Namely, we introduce discrete weighted Laplacians $X_{k,N} : \mathcal{X}_N \rightarrow \mathcal{X}_N$ and $Y_{k,N} : \mathcal{Y}_N \rightarrow \mathcal{Y}_N$ defined by the variational problems

$$\forall \theta, \theta' \in \mathcal{X}_N, \quad (X_{k,N} \theta, \theta')_{\frac{1}{\omega}} = (X_k \theta, \theta')_{\frac{1}{\omega}},$$

$$\forall \nu, \nu' \in \mathcal{Y}_N, \quad (Y_{k,N} \nu, \nu')_{\omega} = (Y_k \nu, \nu')_{\omega},$$

where

$$X_k = -\omega \operatorname{div} \omega \nabla - k^2 \omega^2 - i\varepsilon(k) I_d$$

$$Y_k = -\operatorname{div} \omega \nabla \omega - k^2 \omega^2 - i\eta(k) I_d,$$

for some functions $\varepsilon(k) > 0$ and $\eta(k) > 0$ to be specified later, where i is the imaginary unit and I_d the identity operator. In practice, this addition of a purely imaginary part to the spectrum turns out to be important for the performance of the method. The idea is borrowed from [14], where a similar approach is used to capture the behavior of a Dirichlet-to-Neumann operator on so-called ‘‘grazing modes’’.

Clearly, $X_{k,N}$ and $Y_{k,N}$ are diagonalizable since they are the sum of a Hermitian operator (in the scalar products $(\cdot, \cdot)_{\frac{1}{\omega}}$ and $(\cdot, \cdot)_{\omega}$, respectively) and a multiple of the identity. Hence, using functional calculus, we can define $f(X_{k,N})$ and $g(Y_{k,N})$ for any well-defined functions f and g over the spectrum of $X_{k,N}$ and $Y_{k,N}$. In this sense, let

$$p_k(\theta, \theta') := ((X_{k,N})^{1/2} \theta, \theta')_{\frac{1}{\omega}}, \quad \forall (\theta, \theta') \in \mathcal{X}_N \times \mathcal{X}_N$$

$$q_k(\nu, \nu') := ((Y_{k,N})^{-1/2} \nu, \nu')_{\omega}, \quad \forall (\nu, \nu') \in \mathcal{Y}_N \times \mathcal{Y}_N.$$

The symbol $\sqrt{\cdot}$ here stands for the principal square root, with branch cut along the negative real axis, while for any complex number $z \in \mathbb{C}$, $z^{-1/2}$ is understood as $\sqrt{\bar{z}}/z$.

Let \mathbf{P}_k and \mathbf{Q}_k be the matrices of size $(\dim \mathcal{X}_N) \times (\dim \mathcal{X}_N)$ and $(\dim \mathcal{Y}_N) \times (\dim \mathcal{Y}_N)$ respectively, defined by

$$(\mathbf{P}_k)_{ij} := p_k(\theta_i^N, \theta_j^N), \quad 1 \leq i, j \leq \dim \mathcal{X}_N, \quad (56)$$

$$(\mathbf{Q}_k)_{ij} := q_k(\nu_i^N, \nu_j^N), \quad 1 \leq i, j \leq \dim \mathcal{Y}_N. \quad (57)$$

Then, we define the preconditioners

$$\widehat{\mathbf{P}}_k := \mathbf{D}^{-1} \mathbf{P}_k \mathbf{D}^{-T}, \quad (58)$$

$$\widehat{\mathbf{Q}}_k := \widetilde{\mathbf{D}}^{-T} \mathbf{Q}_k \mathbf{D}^{-1}. \quad (59)$$

The matrices $\mathbf{M}_{X,k}$ and $\mathbf{M}_{Y,k}$ of $X_{k,j}$ and $Y_{k,j}$ in the basis $\{\theta_i\}_{1 \leq i \leq \dim \mathcal{X}_N}$ and $\{\nu_i\}_{1 \leq i \leq \dim \mathcal{Y}_N}$ are respectively given by

$$\mathbf{M}_{X,k} = \mathbf{I}_{\frac{1}{\omega}}^{-1} \left(\mathbf{X}_{\frac{1}{\omega}} - k^2 \mathbf{W}_{\frac{1}{\omega}} - i\varepsilon(k) \mathbf{I}_{\frac{1}{\omega}} \right), \quad \mathbf{M}_{Y,k} = \mathbf{I}_{\omega}^{-1} \left(\mathbf{Y}_{\omega} - k^2 \mathbf{W}_{\omega} - i\eta(k) \mathbf{I}_{\omega} \right),$$

where $\mathbf{X}_{\frac{1}{\omega}}$, $\mathbf{I}_{\frac{1}{\omega}}$, \mathbf{X}_{ω} and \mathbf{I}_{ω} are defined in the two previous subsections, and where $\mathbf{W}_{\frac{1}{\omega}}$ and \mathbf{W}_{ω} are respectively the $(\dim \mathcal{X}_N) \times (\dim \mathcal{X}_N)$ and $(\dim \mathcal{Y}_N) \times (\dim \mathcal{Y}_N)$ square matrices defined by

$$(\mathbf{W}_{\frac{1}{\omega}})_{ij} = \int_{\mathbb{D}} \omega \theta_i^N(x) \theta_j^N(x) dx, \quad (\mathbf{W}_{\omega})_{ij} = \int_{\mathbb{D}} \omega(x)^3 \nu_i^N(x) \nu_j^N(x) dx.$$

We deduce that

$$\mathbf{P}_k = \mathbf{I}_{\frac{1}{\omega}} \sqrt{\mathbf{I}_{\frac{1}{\omega}}^{-1} \left(\mathbf{X}_{\frac{1}{\omega}} - k^2 \mathbf{W}_{\frac{1}{\omega}} - i\varepsilon(k) \mathbf{I}_{\frac{1}{\omega}} \right)} = ik \mathbf{I}_{\frac{1}{\omega}} \sqrt{I_d - \mathbf{I}_{\frac{1}{\omega}}^{-1} \mathbf{A}(k) / k^2},$$

where

$$\mathbf{A}(k) = \left(\mathbf{X}_{\frac{1}{\omega}} + k^2 (\mathbf{I}_{\frac{1}{\omega}} - \mathbf{W}_{\frac{1}{\omega}}) - i\varepsilon(k) \mathbf{I}_{\frac{1}{\omega}} \right).$$

To evaluate the square-root, we can no longer resort to the method of [21] since the spectrum of the matrix under the square root now occupies a region of the complex plane that is not confined to the positive real axis. We instead follow [5] and use the rational approximation of the function $X \mapsto ik\sqrt{1 - X/k^2}$ root developed in [31]. This again takes the form

$$ik\sqrt{1 - X/k^2} \approx a_0(k) + \sum_{q=1}^Q \frac{a_q(k)X}{1 + b_q(k)X}$$

for some explicit (complex) coefficients $a_q(k)$ and $b_q(k)$ (we use the value $\theta = \frac{\pi}{3}$, as advocated in [14], for the branch-cut rotation angle). The domain of convergence and the accuracy of this approximation is discussed in many places, for instance [29]. Choosing $\varepsilon(k) > 0$ ensures that the spectrum of $\mathbf{A}(k)$ is within the zone of convergence of this approximation. In practice, $Q = 15$ terms is more than enough in all of our tests. This leads to

$$\mathbf{P}_k \approx a_0(k) \mathbf{A}(k) + \mathbf{I}_{\frac{1}{\omega}} \sum_{q=1}^Q a_q(k) (\mathbf{I}_{\frac{1}{\omega}} + b_q(k) \mathbf{A}(k))^{-1} \mathbf{A}(k). \quad (60)$$

For \mathbf{Q}_k , we write

$$\mathbf{Q}_k = ik \mathbf{I}_{\omega} (\mathbf{M}_{Y,k})^{-1} \sqrt{I_d - \mathbf{I}_{\omega}^{-1} \mathbf{B}(k) / k^2}$$

where

$$\mathbf{B}(k) = \mathbf{Y}_{\omega} + k^2 (\mathbf{I}_{\omega} - \mathbf{W}_{\omega}) - i\eta(k) \mathbf{I}_{\omega}.$$

This leads to the approximation

$$\mathbf{Q}_k \approx \mathbf{I}_\omega (\mathbf{B}(k) - k^2 I_d)^{-1} \left\{ a_0(k) \mathbf{B}(k) + \mathbf{I}_\omega \sum_{q=1}^Q a_q(k) (\mathbf{I}_\omega + b_q(k) \mathbf{B}(k))^{-1} \mathbf{B}(k) \right\}. \quad (61)$$

Those approximations of \mathbf{P}_k and \mathbf{Q}_k have exactly the same form as Eqs. (51) and (55), so, for the same reason, the matrix vector products $X \mapsto \mathbf{P}_k X$ and $X \mapsto \mathbf{Q}_k X$ can be evaluated cheaply. By trial and error, we have found that the functions

$$\varepsilon(k) = 0.45k, \quad \eta(k) = 0.55k$$

give good result, although, once again, we are unable to provide any theoretical foundation for those choices so far. The fact that the formulas (60) and (61) are well defined, i.e. that the required matrix inverses exist is also left open. This can probably be established by elementary arguments as in [3, Lemma 8]. In our experiments, the matrices to be inverted are always fairly well-conditioned.

5 Numerical Experiments

5.1 Overview

We now present some numerical evidence to support the use of the preconditioners $\widehat{\mathbf{P}}_k$ and $\widehat{\mathbf{Q}}_k$, defined in Eqs. (43), (58), (53) and (59), for the linear systems (36)-(37).

We present results on quasi-uniform meshes as well as on graded meshes, with a grading parameter of $\beta = 2$. For both types of meshes, we use a sequence of 9 refinement levels leading to meshes with over a million vertices. The main characteristics of those meshes are summarized in Tables 1 and 2. For the graded mesh, we report the measure in degree of the smallest angle between two edges of a triangle in the mesh. This is an indicator of the shape-regularity of this sequence of meshes. The uniform and graded meshes of levels 4 and 5 are represented in Figures 1 and 2, respectively. We remind the reader that, due to the singularity of the jumps λ and μ associated to the edge of \mathbb{D} , graded meshes are in theory preferable to uniform meshes in our context to speed-up the convergence of the Galerkin method [26].

| Refinement level | h_{\max} | h_{\min} | Number of vertices | Number of triangles |
|------------------|------------|------------|--------------------|---------------------|
| 1 | 0.47 | 0.29 | 40 | 59 |
| 2 | 0.23 | 0.14 | 136 | 232 |
| 3 | 0.13 | 0.079 | 421 | 770 |
| 4 | 0.067 | 0.041 | 1,462 | 2,790 |
| 5 | 0.034 | 0.021 | 5,431 | 10,602 |
| 6 | 0.017 | 0.011 | 20,907 | 41,303 |
| 7 | 8.7e-3 | 5.4e-3 | 83,038 | 165,056 |
| 8 | 4.4e-3 | 2.7e-3 | 328,935 | 655,838 |
| 9 | 2.2e-3 | 1.3e-3 | 1,313,387 | 2,622,713 |

Table 1: Characteristics of the uniform meshes used in the experiments. The parameter h_{\min} (resp. h_{\max}) is the length of the shortest (resp. longest) edge in the mesh.

| Refinement level | h_{\max} | h_{\min} | θ_{\min} | Number of vertices | Number of triangles |
|------------------|------------|------------|-----------------|--------------------|---------------------|
| 1 | 0.75 | 0.25 | 9.0 | 32 | 37 |
| 2 | 0.47 | 0.0625 | 8.4 | 153 | 204 |
| 3 | 0.34 | 0.020 | 8.2 | 541 | 773 |
| 4 | 0.21 | 6.9e-3 | 8.2 | 1,815 | 2,724 |
| 5 | 0.11 | 2.1e-3 | 8.2 | 69,83 | 10,923 |
| 6 | 0.068 | 6.25e-4 | 8.2 | 26,000 | 41,945 |
| 7 | 0.037 | 1.8e-4 | 8.2 | 99,418 | 164,428 |
| 8 | 0.020 | 5.3e-5 | 8.2 | 376,760 | 635,589 |
| 9 | 0.011 | 1.5e-05 | 8.2 | 1,455,784 | 2,496,568 |

Table 2: Characteristics of the graded meshes used in the experiments. The parameter h_{\min} (resp. h_{\max}) is the length of the shortest (resp. longest) edge in the mesh, while θ_{\min} is the measure in degrees of the smallest angle between two edges of a triangle of the mesh.

To calculate the Galerkin matrices of the layer potentials, we use the Matlab toolbox GypsiLab [2]. The singular integrals are evaluated via semi-analytic methods. On fine meshes, the Galerkin matrices \mathbf{V}_k and \mathbf{W}_k do not fit in memory. In those cases, we use compression by the Fast Multipole Method (both for $k = 0$ and $k > 0$) [19, 37], with the open-source Matlab wrappers of FMMLIB3D [16].

In all cases, the linear systems as well as their preconditioned versions are solved using GMRES [38], restarted every 20 iterations, with a tolerance $\varepsilon_{\text{GMRES}} = 10^{-6}$. We interrupt GMRES if it did not converge after 200 iterations (i.e. 10 outer iterations each consisting of 20 inner iterations). This rather low threshold allows for all the numerical tests presented below to be reproducible in around 3 days of computation.

For $k = 0$, and when the full matrices fit in memory (levels 1-4), we report the condition number κ of both the linear systems matrices and their preconditioned versions. In this case, the Galerkin matrices and their preconditioners are symmetric, so κ governs the speed of convergence of the GMRES iteration.

For large matrices (levels 5-9), computing the condition number is no longer feasible. Besides, for $k > 0$, the Galerkin matrices and their preconditioners are not normal, hence the condition number cannot be used to predict the behavior of GMRES (see e.g. [32]). Hence, in this case, we directly report the number of iterations needed in GMRES. The time it takes to solve iteratively the linear systems highly depends on the machine used for the calculations. Nevertheless, we still report timings for our machine in order to give a rough idea of the speedups that can be expected when using our method. When GMRES does not reach the tolerance after 200 iterations, we report the time taken to perform those 200 iterations, although the system should not be considered as being solved. All floating point numbers are rounded to 2 significant digits.

When the full matrices fit in memory, the computation of the matrix square roots are done using the Matlab function `sqrtm`. For larger matrices and when $k = 0$, we use the approximations (51) and (55) based on [21]. For $k > 0$, we use instead the approximations (60) and (61) based on the rational approximation of $X \mapsto ik\sqrt{1 - X/k^2}$ from [31].

For the matrix \mathbf{W}_k , we compare the performance of our square-root preconditioner with the

Calderón preconditioner [11]*

$$\widehat{\mathbf{C}}_k := \widetilde{\mathbf{D}}^{-T} \widetilde{\mathbf{V}}_k \widetilde{\mathbf{D}}^{-1}, \quad (62)$$

where $\widetilde{\mathbf{V}}_k$ is the Galerkin matrix of the weakly singular operator over the space \mathcal{W}_N , that is, the space of piecewise linear elements on the triangulation \mathcal{T}_N with Dirichlet conditions on $\partial\mathcal{T}_N$. The Calderón preconditioner turns out to be particularly efficient in our tests, probably due to the fact that the screen \mathbb{D} is flat. Indeed, because of this, the double layer potential vanishes on \mathbb{D} , so that, sloppily speaking, i.e. pretending that \mathbb{D} were a smooth closed surface in \mathbb{R}^3 , the Calderón formula [33, Thm 3.1.3] would read

$$V_k W_k = W_k V_k = \frac{1}{4} I_d.$$

5.2 Results

We now report and discuss our numerical results. They are obtained on a computer running on 8 cores with multi-threading, with a clock rate of 3.8GHz, and with 32GB of RAM.

Laplace equation on uniform meshes

In Tables 3-4 below, we report the performance of $\widehat{\mathbf{P}}$ as a preconditioner for \mathbf{V} on a sequence of uniform meshes.

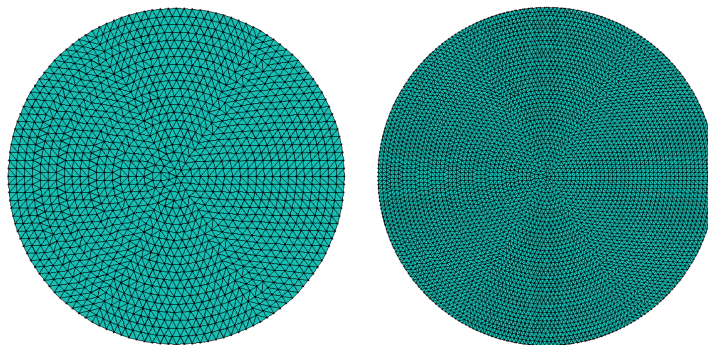


Figure 1: Uniform meshes of levels $n = 4$ (left) and $n = 5$ (right).

| Refinement level | $\kappa(\mathbf{V})$ | $\kappa(\mathbf{D}^{-1}\mathbf{V})$ | $\kappa(\widehat{\mathbf{P}}\mathbf{V})$ |
|------------------|----------------------|-------------------------------------|--|
| 1 | 82.9215 | 13.1953 | 1.3956 |
| 2 | 184.2518 | 26.3687 | 1.411 |
| 3 | 355.0135 | 48.6967 | 1.4514 |
| 4 | 686.7896 | 93.3797 | 1.4814 |

Table 3: Condition numbers of the matrices \mathbf{V} , $\mathbf{D}^{-1}\mathbf{V}$ (mass matrix preconditioner) and $\widehat{\mathbf{P}}\mathbf{V}$ (square-root preconditioner) assembled on uniform meshes.

*We could also consider a Calderón preconditioner for \mathbf{V}_k , but this is slightly less straightforward, since W has a non-trivial kernel on the finite-element space of piecewise linear functions with no Dirichlet conditions on $\partial\mathbb{D}$.

| Refinement level | No prec. | | Square-root prec. | |
|------------------|----------|-------|-------------------|-----|
| | n | t | n | t |
| 5 | 128 | 9.0 | 6 | 2.0 |
| 6 | >200 | 45 | 6 | 6.0 |
| 7 | >200 | 180 | 6 | 26 |
| 8 | >200 | 730 | 6 | 130 |
| 9 | >200 | 2.9e3 | 7 | 785 |

Table 4: Number of iterations n and time t in seconds needed for the iterative resolution of the hypersingular equation (36) for $k = 0$, on uniform meshes, with the right-hand side F_N corresponding to the function $f(x) = 1/\omega(x)$ in Eq. (40). Columns 2-3 and 4-5 correspond to the resolution without preconditioner, and with our square-root preconditioner $\widehat{\mathbf{P}}$, respectively.

Results for the Laplace hypersingular equation on uniform meshes are reported in Tables 5-6 below.

| Refinement level | $\kappa(\mathbf{W})$ | $\kappa(\widetilde{\mathbf{D}}^{-1}\mathbf{W})$ | $\kappa(\widehat{\mathbf{C}}\mathbf{W})$ | $\kappa(\widehat{\mathbf{Q}}\mathbf{W})$ |
|------------------|----------------------|---|--|--|
| 1 | 2.4226 | 6.5229 | 1.8971 | 1.3051 |
| 2 | 4.5353 | 13.8201 | 2.4223 | 1.4149 |
| 3 | 8.3698 | 25.5514 | 3.1051 | 1.488 |
| 4 | 16.0808 | 49.177 | 4.2366 | 1.5601 |

Table 5: Condition numbers of the matrices \mathbf{W} , $\widehat{\mathbf{C}}\mathbf{W}$ (Calderón preconditioner) and $\widehat{\mathbf{Q}}\mathbf{W}$ (square-root preconditioner), assembled on uniform meshes.

| Refinement level | No prec. | | Calderón prec. | | Square-root prec. | |
|------------------|----------|-------|----------------|-----|-------------------|-----|
| | n | t | n | t | n | t |
| 5 | 22 | 3.4 | 7 | 2.2 | 5 | 2.2 |
| 6 | 30 | 15 | 6 | 6.8 | 5 | 6.8 |
| 7 | 57 | 110 | 6 | 29 | 5 | 29 |
| 8 | 107 | 850 | 7 | 140 | 5 | 140 |
| 9 | 183 | 6.0e3 | 7 | 650 | 5 | 740 |

Table 6: Number of iterations n and time t in seconds needed for the iterative resolution of the hypersingular equation (37) for $k = 0$, on uniform meshes, with the right-hand side G_N corresponding to the function $g(x) = \omega(x)$ in Eq. (40). Columns 2-3, 4-5 and 6-7 correspond to the resolution without preconditioner, with the Calderón preconditioner $\widehat{\mathbf{C}}$, and with our square-root preconditioner $\widehat{\mathbf{Q}}$, respectively.

Those results confirm the expectations that $\widehat{\mathbf{P}}$ and $\widehat{\mathbf{Q}}$ are excellent preconditioners for \mathbf{V} and \mathbf{W} on uniform meshes. For levels 1-4, they lead to condition numbers below 2, and for levels 5 – 9, the number of GMRES iterations required to reach the tolerance never exceeds 7. Table 5 highlights the difference with the Calderon preconditioner $\widehat{\mathbf{C}}$, which is known to suffer from the so-called “duality mismatch” (the fact that $H^{1/2}(\mathbb{D})$ and $H^{-1/2}(\mathbb{D})$ are not dual to each other). This property translates into a slow increase in the condition number, see e.g. [11, Proposition 3].

Despite this, the resolution time with the Calderón preconditioner is roughly similar to that of our square-root preconditioners in our setting, with a slight advantage for the former.

Laplace equation on graded meshes

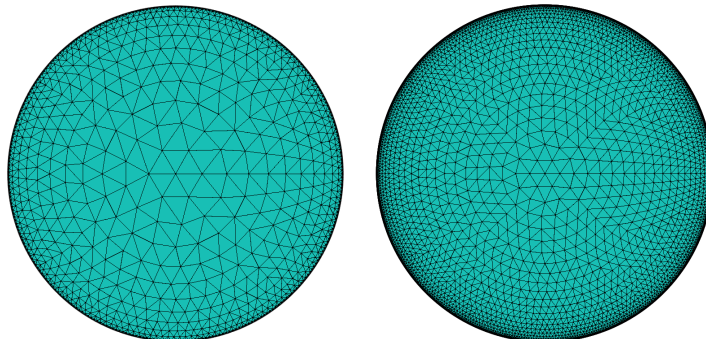


Figure 2: Non-uniform meshes of levels $n = 5$ (left) and $n = 6$ (right).

We report in Tables 7-8 the preconditioning performance for the weakly singular operator on graded meshes.

| Refinement level | $\kappa(\mathbf{V})$ | $\kappa(\mathbf{D}^{-1}\mathbf{V})$ | $\kappa(\hat{\mathbf{P}}\mathbf{V})$ |
|------------------|----------------------|-------------------------------------|--------------------------------------|
| 1 | 700 | 20 | 2.4 |
| 2 | 1.6e4 | 99 | 3.2 |
| 3 | 1.7e5 | 330 | 4.8 |
| 4 | 1.5e6 | 1.0e3 | 9.6 |

Table 7: Condition numbers of the matrices \mathbf{V} , $\mathbf{D}^{-1}\mathbf{V}$ (mass-matrix preconditioner), and $\hat{\mathbf{P}}\mathbf{V}$ (square-root preconditioner) assembled on graded meshes.

From those results, it seems that a result such as Theorem 5 is not verified on our sequence of graded meshes, as the condition number of $\hat{\mathbf{P}}\mathbf{V}$ now seems to increase with mesh refinement. The condition number improvement nevertheless remains drastic, and the number of GMRES iterations required to solve the system on finer levels remains small, as shown in Table 8 below.

| Refinement level | No prec. | | Square-root prec. | |
|------------------|----------|-------|-------------------|-----|
| | n | t | n | t |
| 5 | > 200 | 14 | 7 | 2.3 |
| 6 | > 200 | 50 | 8 | 7.1 |
| 7 | > 200 | 200 | 8 | 28 |
| 8 | > 200 | 750 | 8 | 120 |
| 9 | > 200 | 3.1e3 | 8 | 530 |

Table 8: Number of iterations n and resolution time t in seconds for the iterative resolution of the weakly singular equation (36) for $k = 0$ on graded meshes, with the right-hand side F_N corresponding to the function $f(x) = 1/\omega(x)$ in Eq. (40). Columns 2-3 and 4-5 correspond to the resolution without preconditioner, and with our square-root preconditioner $\hat{\mathbf{P}}$, respectively.

Notice that without preconditioner, the desired tolerance is never reached with 200 iterations. The weakly singular operator is so ill-conditioned on the graded meshes that the GMRES residuals almost stagnate. On the finest levels, the required number of iterations is probably much larger than 200, so the speedup allowed by our preconditioners is underestimated by the figures of Table 8.

In Tables 9-10, we report the results concerning the hypersingular operator.

| Refinement level | $\kappa(\mathbf{W})$ | $\kappa(\hat{\mathbf{Q}}\mathbf{W})$ | $\kappa(\hat{\mathbf{C}}\mathbf{W})$ |
|------------------|----------------------|--------------------------------------|--------------------------------------|
| 1 | 1.4 | 1.2 | 1.7 |
| 2 | 3.3 | 1.3 | 2.5 |
| 3 | 7.45 | 1.4 | 3.3 |
| 4 | 15 | 1.4 | 4.1 |

Table 9: Condition numbers of the matrices \mathbf{W} , $\hat{\mathbf{C}}\mathbf{W}$ (Calderón preconditioner), and $\hat{\mathbf{Q}}\mathbf{W}$ (square-root preconditioner) assembled on graded meshes.

| Refinement level | No prec. | | Calderón prec. | | Square-root prec. | |
|------------------|----------|-------|----------------|-----|-------------------|-----|
| | n | t | n | t | n | t |
| 5 | 38 | 5.6 | 9 | 2.5 | 5 | 2.0 |
| 6 | 58 | 31.7 | 10 | 10 | 5 | 6.0 |
| 7 | 86 | 180 | 10 | 41 | 5 | 24 |
| 8 | 131 | 1.1e3 | 11 | 180 | 5 | 100 |
| 9 | > 200 | 6.5e3 | 12 | 820 | 5 | 430 |

Table 10: Number of iterations n and time t in seconds needed for the iterative resolution of the hypersingular equation (37) for $k = 0$, on graded meshes, with the rhs G_N corresponding to the function $g(x) = \omega(x)$ in Eq. (40). Columns 2-3, 4-5 and 6-7 correspond to the resolution without preconditioner, with the Calderón preconditioner $\hat{\mathbf{C}}$, and with our square-root preconditioner $\hat{\mathbf{Q}}$, respectively.

In contrast to the case of the weakly-singular equation, the preconditioner $\hat{\mathbf{Q}}$ seems to lead to a uniformly bounded condition number even on graded meshes. The difference with the Calderón is again noticeable, and this time, it is also reflected in the resolution time. On the finest graded mesh,

the square-root preconditioner speeds up the resolution by a factor 2 compared to the Calderón preconditioner, and allows to solve a problem on a mesh with 2.5 millions of elements in less than 10 minutes (while almost 2 hours without preconditioner weren't enough to reach the desired tolerance).

Helmholtz equation on uniform meshes

We now turn our attention to the case of a non-zero wavenumber $k > 0$. In what follows, we have chosen $k = 1/(2h_{\max})$ for the uniform meshes, and $k = 1/h_{\max}$ for the graded meshes, where h_{\max} is the length of the longest edge in the mesh. With those choices, the mesh accurately represents the wavelengths as small as $2\pi/k$. In Table 11 below, we report the preconditioning performance for the weakly singular operator. We consider the scattering by \mathbb{D} of a plane wave of wavenumber k illuminating the disk with an angle $\pi/4$ with respect to the vertical axis. In other words, the right-hand sides of Eqs. (36) and (37) are chosen as Dirichlet and Neumann traces, respectively, of the plane wave

$$\forall x \in \mathbb{R}^3, \quad u_{\text{inc}}(x) := e^{ik \frac{x_1 + x_3}{\sqrt{2}}}. \quad (63)$$

We report the results on uniform meshes in Table 11 (weakly-singular operator) and Table 12 (hypersingular operator) below.

| Refinement level | k | n_1 | t_1 | n_2 | t_2 |
|------------------|------|-------|-------|-------|-------|
| 1 | 2.1 | 23 | 0.1 | 7 | 0.5 |
| 2 | 4.25 | 49 | 0.6 | 7 | 0.8 |
| 3 | 7.8 | 92 | 2.8 | 7 | 1.0 |
| 4 | 15 | 110 | 8.9 | 8 | 1.8 |
| 5 | 29 | 133 | 45 | 8 | 5.2 |
| 6 | 57 | 157 | 210 | 9 | 23 |
| 7 | 115 | 191 | 1.1e3 | 12 | 145 |
| 8 | 228 | 222 | 5.8e3 | 18 | 960 |
| 9 | 457 | 263 | 2.9e4 | - | - |

Table 11: Number of iterations n and resolution time t in seconds for the iterative resolution of the weakly singular equation (36) on uniform meshes, with the right-hand side F_N corresponding to the Dirichlet trace of the plane wave (63). Columns 2-3 and 4-5 correspond to the resolution without preconditioner, and with our square-root preconditioner $\widehat{\mathbf{P}}_k$, respectively.

| Refinement level | k | n_1 | t_1 | n_2 | t_2 | n_3 | t_3 |
|------------------|------|-------|--------|-------|-------|-------|-------|
| 1 | 1.45 | 6 | 0.1 | 4 | 0.5 | 5 | 0.1 |
| 2 | 2.1 | 9 | 0.1 | 6 | 0.5 | 7 | 0.1 |
| 3 | 4.25 | 15 | 0.6 | 7 | 0.8 | 8 | 0.51 |
| 4 | 7.8 | 30 | 3.0 | 8 | 1.8 | 9 | 1.3 |
| 5 | 15 | 38 | 9.4 | 8 | 3.8 | 9 | 3.6 |
| 6 | 29 | 45 | 46 | 10 | 14.5 | 8 | 14 |
| 7 | 57 | 52 | 220 | 12 | 69 | 8 | 54 |
| 8 | 115 | 60 | 1.0e3 | 17 | 420 | 7 | 210 |
| 9 | 228 | 70 | 5.15e3 | 25 | 2.9e3 | 7 | 900 |
| 10 | - | - | - | - | - | - | - |

Table 12: Number of iterations n and resolution time t in seconds for the iterative resolution of the hypersingular equation (37) on uniform meshes, with the right-hand side G_N corresponding to the Neumann trace of the plane wave (63). Columns 2-3, 4-5 and 6-7 correspond to the resolution without preconditioner, with the Calderón preconditioner $\widehat{\mathbf{C}}_k$ and with our square-root preconditioner $\widehat{\mathbf{Q}}_k$, respectively.

The results of this section demonstrate the robustness of our preconditioners with respect to the wavenumber on uniform meshes. However, in Table 12, we see that the Calderón preconditioner still performs better than our square-root preconditioner, both from the point of view of resolution time and number of iterations.

Helmholtz equation on non-uniform meshes

We now report results for the Helmholtz equation on graded meshes.

| Refinement level | k | No prec. | | Square-root prec. | |
|------------------|-----|----------|-------|-------------------|-------|
| | | n | t | n | t |
| 1 | 1.3 | 17 | 0.1 | 8 | 0.8 |
| 2 | 2.1 | > 200 | 1.3 | 8 | 0.9 |
| 3 | 2.9 | > 200 | 4.0 | 8 | 1.5 |
| 4 | 4.7 | > 200 | 9.4 | 8 | 2.2 |
| 5 | 8.5 | > 200 | 41 | 8 | 4.6 |
| 6 | 15 | > 200 | 160 | 8 | 16 |
| 7 | 27 | > 200 | 630 | 8 | 64 |
| 8 | 50 | > 200 | 2.4e3 | 8 | 280 |
| 9 | 91 | > 200 | 9.5e3 | 9 | 1.3e3 |

Table 13: Number of iterations n and resolution time t in seconds for the iterative resolution of the weakly singular equation (36) on graded meshes, with the right-hand side F_N corresponding to the Dirichlet trace of the plane wave (63). Columns 2-3 and 4-5 correspond to the resolution without preconditioner, and with our square-root preconditioner $\widehat{\mathbf{P}}_k$, respectively.

| Refinement level | k | No prec. | | Calderón prec. | | Square-root prec. | |
|------------------|-----|----------|-------|----------------|-------|-------------------|-------|
| | | n | t | n | t | n | t |
| 1 | 1.3 | 5 | 0.1 | 4 | 0.1 | 5 | 0.6 |
| 2 | 2.1 | 12 | 0.1 | 8 | 0.3 | 6 | 0.9 |
| 3 | 2.9 | 20 | 1.0 | 9 | 0.9 | 6 | 1.6 |
| 4 | 4.7 | 36 | 5.0 | 11 | 2.4 | 6 | 2.4 |
| 5 | 8.5 | 84 | 51 | 11 | 10 | 7 | 7.4 |
| 6 | 15 | 137 | 320 | 12 | 43 | 7 | 26 |
| 7 | 27 | > 200 | 1.9e3 | 12 | 170 | 7 | 110 |
| 8 | 50 | > 200 | 7.2e3 | 12 | 670 | 8 | 480 |
| 9 | 91 | > 200 | 2.9e4 | 12 | 2.7e3 | 9 | 2.3e3 |

Table 14: Number of iterations n and resolution time t in seconds for the iterative resolution of the hypersingular equation (37) on graded meshes, with the rhs G_N corresponding to the Neumann trace of the plane wave (63). Columns 2-3, 4-5 and 6-7 correspond to the resolution without preconditioner, with the Calderón preconditioner $\widehat{\mathbf{C}}_k$ and with our square-root preconditioner $\widehat{\mathbf{Q}}_k$, respectively.

The performance of our preconditioners on graded meshes seems to be even better than on uniform meshes. In this case, our square-root preconditioner outperforms the Calderón preconditioner.

Different corrections

Finally, we would like to illustrate the practical importance of the corrective term $-k^2\omega^2$ in the definitions P_k and Q_k . For this, we compare our preconditioner P_k with three alternatives. The first one is $\widehat{\mathbf{P}}$ (the preconditioner used for $k = 0$). The second and third ones are based on the operators

$$T_k := \frac{1}{\omega} (-\omega \operatorname{div} \omega \nabla - k^2 \operatorname{Id})^{\frac{1}{2}}, \quad \Lambda_k := (-\Delta - k^2 \operatorname{Id})^{\frac{1}{2}} \quad (64)$$

The operators T_k and Λ_k are converted into preconditioners $\widehat{\mathbf{T}}_k$ and $\widehat{\mathbf{\Lambda}}_k$ for \mathbf{V}_k in the same way as $\widehat{\mathbf{P}}_k$ is derived from \mathbf{P}_k , see Section 4. Using $\widehat{\mathbf{P}}$ in place of $\widehat{\mathbf{P}}_k$ amounts to ignoring the k -dependency of \mathbf{V}_k . The preconditioner $\widehat{\mathbf{T}}_k$ is a naive attempt to include a k -dependency in the preconditioner. Finally, the preconditioner $\widehat{\mathbf{\Lambda}}_k$ corresponds to the approximation of the DtN map from [5] for a smooth surface. Using this preconditioner amounts to ignoring the edge singularity of the screen by formally putting $\omega \equiv 1$.

We report the performance of those preconditioners on uniform and graded meshes in Table 15 below.

| Uniform meshes | | | | | | Graded meshes | | | | | |
|----------------|------|---------------------------------|-------------------------------|---------------------------------|---------------------------------------|---------------|-----|---------------------------------|-------------------------------|---------------------------------|---------------------------------------|
| Level | k | $\widehat{\mathbf{P}}_k$ n | $\widehat{\mathbf{P}}$ n | $\widehat{\mathbf{T}}_k$ n | $\widehat{\mathbf{\Lambda}}_k$ n | Level | k | $\widehat{\mathbf{P}}_k$ n | $\widehat{\mathbf{P}}$ n | $\widehat{\mathbf{T}}_k$ n | $\widehat{\mathbf{\Lambda}}_k$ n |
| 1 | 1.1 | 8 | 7 | 10 | 10 | 1 | 1.3 | 8 | 8 | 10 | 10 |
| 2 | 2.1 | 8 | 8 | 15 | 11 | 2 | 2.1 | 8 | 10 | 16 | 15 |
| 3 | 3.9 | 7 | 11 | 26 | 12 | 3 | 2.9 | 8 | 11 | 20 | 19 |
| 4 | 7.4 | 8 | 21 | 44 | 13 | 4 | 4.7 | 8 | 14 | 30 | 28 |
| 5 | 14.5 | 8 | 51 | 68 | 15 | 5 | 8.5 | 8 | 35 | 51 | 38 |
| 6 | 29 | 7 | 87 | 95 | 17 | 6 | 15 | 8 | 53 | 78 | 56 |
| 7 | 57 | 7 | 157 | 128 | 20 | 7 | 27 | 8 | 99 | 116 | 89 |
| 8 | 115 | 8 | > 200 | 152 | 25 | 8 | 50 | 8 | 163 | > 200 | 143 |

Table 15: Number of iterations n for the iterative resolution of the weakly-singular equation (37) on uniform meshes (left) and graded meshes (right), with the right-hand side F_N corresponding to the Dirichlet trace of the plane wave (63). In each table, columns 3, 4, 5 and 6 correspond to the resolution with the preconditioners, $\widehat{\mathbf{P}}_k$, $\widehat{\mathbf{P}}$, $\widehat{\mathbf{T}}_k$ and $\widehat{\mathbf{\Lambda}}_k$, respectively.

The results clearly show that, among other attempts, our square-root preconditioner is the most robust both to the increase of the condition number and to mesh grading.

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A Proof of Theorem 2

We remark that the identity on associated Legendre polynomials P_l^m (see [1, Eq. (8.5.3)])

$$\forall t \in \mathbb{R}, \quad tP_l^m(t) = \frac{1}{(2l+1)} \left((l+1-m)P_{l+1}^m(t) + (l+m)P_{l-1}^m(t) \right),$$

permits us to deduce a simple algebraic property that connects the functions (T_l^m) and (U_l^m) .

Lemma 18. *For all $(l, m) \in \Lambda$ there holds*

$$T_l^m = j_{l+1}^m U_l^m + j_l^m U_{l-2}^m \quad (65)$$

$$U_l^m = \frac{j_{l+2}^m T_{l+2}^m + j_{l+1}^m T_l^m}{\omega^2} \quad (66)$$

where

$$j_l^m = \begin{cases} 0 & \text{if } l = 0, \\ \sqrt{\frac{l^2 - m^2}{4l^2 - 1}} & \text{otherwise,} \end{cases} \quad (67)$$

and taking the convention $U_{-2}^m = U_{-1}^m = 0$ in Eq. (65).

We omit the proof of this lemma which is a simple calculation. We deduce

Lemma 19. *For all $s \geq 0$, \mathcal{T}^s is continuously embedded in \mathcal{U}^s .*

Proof. We define a map $I : \mathcal{T} \rightarrow \mathcal{U}$ by

$$I \left(\sum_{(l,m) \in \Lambda} \hat{u}_l^m T_l^m \right) = \sum_{(l,m) \in \Lambda} (j_{l+1}^m \hat{u}_l^m + j_{l+2}^m \hat{u}_{l+2}^m) U_l^m,$$

with the coefficients j_l^m given in Eq. (67). The map I is continuous from \mathcal{T}^s to \mathcal{U}^s for all $s \in \mathbb{R}$ since for all $(l, m) \in \Lambda$, one has $|j_l^m| \leq 1$. Moreover, by Eq. (65), I coincides with the identity operator $\text{Id} : L_{\omega}^2 \rightarrow L_{\omega}^2$ on the dense subset of L_{ω}^2 consisting of finite linear combinations of the functions $\{T_l^m\}_{(l,m) \in \Lambda}$. Hence, $Iu = u$ for all $u \in L_{\omega}^2 \supset \mathcal{T}^s$, and the result follows. \square

Next, we establish continuous inclusions $\mathcal{U}^s \subset \mathcal{T}^{s-1}$ for $s \geq 1$. This turns out to be more delicate: roughly speaking, we need to proceed to the inversion of the formula (65) expressing T_l^m in terms of U_l^m and U_{l-2}^m , with careful estimation of the underlying coefficients. We start with the following technical lemma:

Lemma 20.

1. *Let $(l, m) \in \Lambda$. Then*

$$U_l^m = \sum_{\substack{k=|m| \\ l-k \text{ even}}}^l (-1)^{\frac{l-k}{2}} \kappa_{l,m,k} T_k^m \quad (68)$$

where the coefficients $\kappa_{l,m,k}$ are defined whenever $|m| \leq k \leq l$ and l, k and m all share the same parity, as follows.

- For all $(l, m) \in \Lambda$,

$$\kappa_{l,m,l} = \frac{1}{j_{l+1}^m} \quad (69)$$

- For all $|m| \leq k \leq l$ such that k, l and m have the same parity,

$$\kappa_{l+2,m,k} = \frac{j_{l+2}^m}{j_{l+3}^m} \kappa_{l,m,k}. \quad (70)$$

Thus,

$$\kappa_{l,m,k} = \left(\prod_{\substack{\nu=k+2 \\ l-\nu \text{ even}}}^l j_\nu^m \right) \left(\prod_{\substack{\nu=k \\ l-\nu \text{ even}}}^l j_{\nu+1}^m \right)^{-1}. \quad (71)$$

2. For all $|m| \leq k \leq l-2$ with k, l, m of the same parity, there holds

$$\kappa_{l,m,k} = \frac{j_{k+2}^m}{j_{k+1}^m} \kappa_{l,m,k+2}. \quad (72)$$

3. These coefficients satisfy

$$\kappa_{l,m,k} \leq \begin{cases} \frac{1}{j_{k+1}^m} & \text{if } m \neq 0, \\ 2 & \text{if } m = 0. \end{cases}$$

Proof. The formula (68) is readily obtained by induction by combining Eq. (65) with Eqs. (69) and (70). The formula (71) can be easily proven by induction from Eqs. (69) and (70). From (71), (72) follows immediately. Then, writing

$$\begin{aligned} (j_{l+1}^m)^2 &= \frac{(l+1)^2 - m^2}{(2l+1)(2l+3)} \\ &= \frac{1}{4} + \left(\frac{1}{4} - m^2 \right) \frac{1}{(2l+1)(2l+3)} \end{aligned}$$

defined when $(l+1) \geq |m|$, we notice that for $m \neq 0$ (resp. $m = 0$), the sequence $(j_{l+1}^m)_l$ increases (resp. decreases) with respect to l . We deduce, since

$$\frac{\kappa_{l+2,m,k}}{\kappa_{l,m,k}} = \frac{j_{l+2}^m}{j_{l+3}^m},$$

that for $m \neq 0$, the sequence $(\kappa_{l,m,k})_l$ decreases with respect to l , and thus

$$\kappa_{l,m,k} \leq \kappa_{k,m,k} = \frac{1}{j_{k+1}^m}.$$

For $m = 0$, we can write

$$\kappa_{l,0,k} = \frac{1}{j_{l+1}^0} \left(\frac{j_l^0}{j_{l-1}^0} \right) \cdots \left(\frac{j_{k+2}^0}{j_{k+1}^0} \right) \leq \frac{1}{j_{l+1}^0} \leq \lim_{l \rightarrow \infty} \frac{1}{j_{l+1}^0} = 2. \quad \square$$

We further need two intermediate results. The first is a more explicit estimate of $\kappa_{l,m,k}$ presented in the following lemma.

Lemma 21. *For all integers such that $\kappa_{l,m,k}$ is defined, there holds*

$$\kappa_{l,m,k} \leq 2 \frac{\sqrt{(l+1)(l+2) - m^2}}{l+1 - |m|}. \quad (73)$$

Proof. Only the case $m \neq 0$ deserves attention. By Equation 20 above, $\kappa_{l,m,k} \leq \frac{1}{j_{k+1}^m} \leq \frac{1}{j_{l+1}^m}$ since j_l^m is increasing with respect to l . We then write

$$\frac{1}{j_{l+1}^m} = \sqrt{\frac{(2l+1)(2l+3)}{(l+1)^2 - m^2}} \leq \frac{2(l+1)\sqrt{(l+1)^2 - m^2}}{(l+1)^2 - m^2} \leq 2 \frac{\sqrt{(l+1)^2 - m^2}}{l+1 - |m|}$$

from which (73) follows. \square

Second, we need an adjoint Cesarò estimate. It is well-known that the Cesarò operator K defined for $v \in l^2(\mathbb{N}^*)$ by

$$(Kv)_n = \frac{1}{n} \sum_{k=1}^n v_k,$$

is continuous in $l^2(\mathbb{N}^*)$. Therefore, its adjoint K^* , defined by

$$(K^*v)_n = \sum_{k=n}^{+\infty} \frac{v_k}{k},$$

is also continuous. Hence, there exists a constant $C_K > 0$ such that for all $v \in l^2(\mathbb{N})$, there holds

$$\sum_{n=1}^{+\infty} \left| \sum_{k=n}^{+\infty} \frac{v_k}{k} \right|^2 \leq C_K \|v\|_{l^2}^2.$$

Here we rewrite this inequality for sequences v of the form $(v_l)_{l \geq |m|}$. In this case, one can check by manipulations on the indices that the previous implies

$$\sum_{l=|m|}^{+\infty} \left| \sum_{k=l}^{+\infty} \frac{v_k}{k+1-|m|} \right|^2 \leq C'_K \sum_{l=|m|}^{+\infty} |v_l|^2 \quad (74)$$

for some constant $C'_K > 0$ independent of m . We are now in a position to prove the inclusion of \mathcal{U}^s into \mathcal{T}^{s-1} for $s \geq 1$:

Lemma 22. *For all $s \geq 1$, \mathcal{U}^s is continuously embedded in \mathcal{T}^{s-1} .*

Proof. Let $s > \frac{1}{2}$. To $u \in \mathcal{U}^s$ given by

$$u = \sum_{(l,m) \in \Lambda} \beta_l^m U_l^m,$$

we associate the element $\tilde{I}u$ of \mathcal{T} defined by

$$\tilde{I}u := \sum_{(l,m) \in \Lambda} \alpha_l^m T_l^m,$$

where

$$\alpha_k^m = \sum_{\substack{l=k \\ l-k \text{ even}}}^{+\infty} (-1)^{\frac{l-k}{2}} \kappa_{l,m,k} \beta_l^m. \quad (75)$$

We claim that for all $s > \frac{1}{2}$, \tilde{I} maps \mathcal{U}^s to \mathcal{T}^{s-1} continuously and satisfies

$$\forall u \in \mathcal{U}^s, \quad I\tilde{I}u = u, \quad (76)$$

where I is the operator defined in Lemma 19.

Firstly, the sum on the rhs of Eq. (75) converges absolutely for $s > \frac{1}{2}$. Indeed, applying Lemma 20 and the Cauchy-Schwarz inequality, we have

$$\sum_{\substack{l=k \\ l-k \text{ even}}}^{+\infty} \left| (-1)^{\frac{l-k}{2}} \kappa_{l,m,k} \beta_l^m \right| \leq \frac{1}{j_{k+1}^m} \sqrt{\sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} [(l+1)(l+2) - m^2]^s |\beta_l^m|^2} \sqrt{\sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} [(l+1)(l+2) - m^2]^{-s}}.$$

The first sum is $\|u\|_{\mathcal{U}^s}$, and the second one is finite for $s > \frac{1}{2}$. This shows that $\tilde{I}u$ is well-defined.

Secondly, one has for all $(k, m) \in \Lambda$,

$$\begin{aligned} j_{k+1}^m \alpha_k^m + j_{k+2}^m \alpha_{k+2}^m &= j_{k+1}^m \left(\sum_{\substack{l=k \\ l-k \text{ even}}}^{+\infty} (-1)^{\frac{l-k}{2}} \kappa_{l,m,k} \beta_l^m \right) + j_{k+2}^m \left(\sum_{\substack{l=k+2 \\ l-k \text{ even}}}^{+\infty} (-1)^{\frac{l-k-2}{2}} \kappa_{l,m,k+2} \beta_l^m \right) \\ &= j_{k+1}^m \kappa_{k,m,k} \beta_k^m + \sum_{\substack{l=k+2 \\ k-l \text{ even}}}^{+\infty} (-1)^{\frac{l-k}{2}} [j_{k+1}^m \kappa_{l,m,k} - j_{k+2}^m \kappa_{l,m,k+2}] \beta_l^m \\ &= \beta_k^m \end{aligned}$$

using Eq. (72) and the definition of $\kappa_{k,m,k}$. This proves the identity (76).

Finally, we write

$$\begin{aligned} \|\tilde{I}u\|_{\mathcal{T}^{s-1}}^2 &= \sum_{m=0}^{+\infty} \sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} \left(\frac{1}{4} + l(l+1) - m^2 \right)^{s-1} |\alpha_l^m|^2 \\ &= \sum_{m=0}^{+\infty} \sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} \left(\frac{1}{4} + l(l+1) - m^2 \right)^{s-1} \left| \sum_{\substack{k=l \\ k-l \text{ even}}}^{+\infty} (-1)^{\frac{k-l}{2}} \kappa_{k,m,l} \beta_k^m \right|^2 \\ &\leq 4 \sum_{m=0}^{+\infty} \sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} \left(\sum_{\substack{k=l \\ k-l \text{ even}}}^{+\infty} ((k+1)(k+2) - m^2)^{\frac{s-1}{2}} \frac{\sqrt{(k+1)(k+2) - m^2}}{k+1-|m|} |\beta_k^m| \right)^2 \end{aligned}$$

using the inequality (73) and the simple estimate

$$\frac{1}{4} + l(l+1) - m^2 \leq (l+1)(l+2) - m^2 \leq (k+1)(k+2) - m^2$$

valid for $l \leq k$. We deduce

$$\begin{aligned} \|\tilde{I}u\|_{\mathcal{T}^{s-1}}^2 &\leq 4 \sum_{m=0}^{+\infty} \sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} \left| \sum_{\substack{k=l \\ k-l \text{ even}}}^{+\infty} ((k+1)(k+2) - m^2)^{\frac{s}{2}} \frac{|\beta_k^m|}{k+1-|m|} \right|^2 \\ &\leq 4C'_K \sum_{m=0}^{+\infty} \sum_{\substack{l=|m| \\ l-m \text{ even}}}^{+\infty} [(l+1)(l+2) - m^2]^s |\beta_l^m|^2 \\ &= 4C'_K \|u\|_{\mathcal{U}^s}^2 \end{aligned}$$

where we applied the adjoint Cesarò estimate (74) with $v_k = ((k+1)(k+2) - m^2)^{\frac{s}{2}} |\beta_k^m|$. This proves the claimed continuity.

For $s \geq 1$, we have shown in Lemma 19 that I coincides with Id on \mathcal{T}^{s-1} . Thus, Eq. (76) states nothing else than

$$\tilde{I}u = u,$$

and the lemma is proved. \square

Remark 1. *At this point, it looks very natural to identify an element $u \in \mathcal{T}^s$ to the element $v \in \mathcal{U}^s$ defined by $v = Iu$. This would make $\mathcal{T}^{-\infty}$ a subspace of $\mathcal{U}^{-\infty}$ and we would have the continuous inclusions $\mathcal{T}^s \subset \mathcal{U}^s$ for all $s \in \mathbb{R}$, and $\mathcal{U}^s \subset \mathcal{T}^{s-1}$ for all $s > \frac{1}{2}$. However, there is a fatal flaw in this reasoning, which is that $I : \mathcal{T}^s \rightarrow \mathcal{U}^s$ is not injective for all $s \in \mathbb{R}$. A good way to see this is by looking at the element $u = \frac{1}{\omega} \in \mathcal{U}^0$, and letting*

$$v := (\omega \partial_{x_1} \omega) u.$$

By Lemma 7, $v \in \mathcal{T}^{-1}$, and by definition of $\omega \nabla \omega$, one has

$$\begin{aligned} \hat{v}_l^m &= 2 \left((\omega \partial_{x_1} \omega) \frac{1}{\omega}, T_l^m \right)_{\frac{1}{\omega}} \\ &= -2 \left(\frac{1}{\omega}, \partial_{x_1} T_l^m \right)_{\omega} \\ &= -2 \int_{\mathbb{D}} \partial_{x_1} \overline{T_l^m(x)} dx \\ &= -2 \int_{\partial \mathbb{D}} \xi_1 \overline{T_l^m(\xi)} d\xi. \end{aligned}$$

One can check that \hat{v}_l^m is not 0 for example for $l = m = 1$ (notice how v is “supported on $\partial \mathbb{D}$ ”, in the sense that $(v, f)_{\frac{1}{\omega}} = 0$ whenever f vanishes on $\partial \mathbb{D}$). Now, let $w = Iv$. For all $(l, m) \in \Lambda$, we

have by definition

$$\begin{aligned}
\check{w}_l^m &= j_{l+1}^m \hat{v}_l^m + j_{l+2}^m \hat{v}_{l+2}^m \\
&= -2 \int_{\partial \mathbb{D}} \xi_1 (j_{l+1}^m \overline{T}_l^m + j_{l+2}^m \overline{T}_{l+2}^m) d\xi \\
&= -2 \int_{\partial \mathbb{D}} \xi_1 \omega^2(\xi) \overline{U}_l^m(\xi) d\xi \\
&= 0
\end{aligned}$$

where we used the identity (68) and the fact that the weight ω vanishes on $\partial \mathbb{D}$. Hence $w = 0$ so I is not injective on \mathcal{T}^{-1} . In fact, one should not view I as an identity operator, but rather as a restriction operator from $\overline{\mathbb{D}}$ to \mathbb{D} . Its kernel contains elements of \mathcal{T}^s supported in $\partial \mathbb{D}$. For $s \geq 0$, this kernel is simply $\{0\}$, but it can be larger for general s (just like for $s \leq -1/2$, the set of distributions of $H^s(\Omega)$ supported in $\partial \Omega$ is strictly larger than $\{0\}$).

Proof of Theorem 2. The inclusions shown above imply at once that $\mathcal{T}^\infty = \mathcal{U}^\infty$. By Lemma 3, $C^\infty(\overline{\mathbb{D}}) \subset \mathcal{T}^\infty$. To show the converse inclusion, we first remark that if $u \in \mathcal{T}^\infty$, then the decomposition of u on the functions T_l^m converges uniformly, as can be seen using the estimate (6). This implies that $\mathcal{T}^\infty \subset C^0$. Furthermore, by Lemma 7, if $u \in \mathcal{T}^\infty$, each component of ∇u is in $\mathcal{U}^\infty = \mathcal{T}^\infty$ and is therefore continuous. The proof is then concluded by a bootstrap argument. \square

B Proof of Theorem 4

Proof. We observe that $\omega \operatorname{div} \omega \nabla$ is a self adjoint operator with respect to the scalar product $(\cdot, \cdot)_{\frac{1}{\omega}}$. Therefore, for any $u \in C^\infty(\overline{\mathbb{D}})$, one has

$$\begin{aligned}
V_{k,\omega}(\omega \operatorname{div} \omega \nabla u) &= \int_{\mathbb{D}} \frac{G_k(x-y) (\omega(y) \nabla_y \cdot (\omega(y) \nabla_y)) u(y)}{\omega(y)} d\sigma_y \\
&= \int_{\mathbb{D}} \frac{(\omega_y \operatorname{div}_y \omega_y \nabla_y G_k)(x-y) u(y)}{\omega(y)} d\sigma_y.
\end{aligned}$$

Let us denote

$$[V_{k,\omega}, \Delta_\omega] = V_{k,\omega}(\omega \operatorname{div} \omega \nabla) u - (\omega \operatorname{div} \omega \nabla) V_{k,\omega} u.$$

The previous computations then lead to

$$[V_{k,\omega}, \Delta_\omega] u = \int_{\mathbb{D}} \frac{\Delta(x,y) u(y)}{\omega(y)} d\sigma_y$$

with

$$\Delta(x,y) = [\omega_y \operatorname{div}_y \omega_y \nabla_y - \omega_x \operatorname{div}_x \omega_x \nabla_x] G_k(x-y).$$

Using now the expression

$$\omega \operatorname{div} \omega \nabla \phi(x) = \omega^2(x) \Delta \phi(x) - x \cdot \nabla \phi(x)$$

we obtain

$$\Delta(x,y) = \Delta_x G_k(x-y) (\omega(y)^2 - \omega(x)^2) + (x+y) \cdot \nabla_x G_k(x-y). \quad (77)$$

We stress the fact that the Laplacian Δ_x used until now is the *bidimensional* Laplacian, which should not be mistaken with the *three dimensional* Laplacian of the Helmholtz equation, that we shall denote by Δ^{3D} . The Green function $G_k(x)$ satisfies the Helmholtz equation

$$\Delta_x^{3D} G_k + k^2 G_k = \delta_0$$

where δ_0 is the Dirac mass at 0. Since G_k is a radial function, we may rewrite this latter equation, with a slight abuse of notation, as

$$G_k''(r) + \frac{2}{r} G_k'(r) + k^2 G_k(r) = \delta_0.$$

We deduce that

$$\begin{aligned} \nabla_x G_k(x) &= G_k'(r) \frac{x}{r} \\ &= -x(G_k''(r) + \frac{1}{r} G_k'(r) + k^2 G_k(r) - \delta_0) \\ &= -x(\Delta_x G_k(x) + k^2 G_k(x)) \end{aligned}$$

with $r = \|x\|$, using that $x\delta_0 = 0$. Plugging this expression in (77), we are led to

$$\Delta(x, y) = (\omega^2(y) - \omega^2(x) + \|y\|^2 - \|x\|^2) \Delta_x G_k(x - y) + k^2(\|y\|^2 - \|x\|^2) G_k(x - y).$$

Since $\omega(x) = \sqrt{1 - \|x\|^2}$, the first term vanishes, and, remarking that $\|y\|^2 - \|x\|^2 = \omega^2(x) - \omega^2(y)$, we may write

$$\begin{aligned} [V_{k,\omega}, \Delta_\omega] u &= k^2 \int_D \frac{(\omega^2(x) - \omega^2(y)) G_k(x - y) u(y)}{\omega(y)} d\sigma_y \\ &= k^2 (\omega^2 V_{k,\omega} - V_{k,\omega} \omega^2) u \end{aligned}$$

which proves the claim. □