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Marion Darbas, Frédérique Le Louër. Well-conditioned boundary integral formulations for high-frequency elastic scattering problems in three dimensions. *Mathematical Methods in the Applied Sciences*, 2015, 38 (9), pp.1705-1733. 10.1002/mma.3179 . hal-00839653v4

**HAL Id: hal-00839653**

**<https://hal.science/hal-00839653v4>**

Submitted on 13 Apr 2014

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# WELL-CONDITIONED BOUNDARY INTEGRAL FORMULATIONS FOR HIGH-FREQUENCY ELASTIC SCATTERING PROBLEMS IN THREE DIMENSIONS

MARION DARBAS AND FRÉDÉRIQUE LE LOUËR

**ABSTRACT.** We construct and analyze a family of well-conditioned boundary integral equations for the Krylov iterative solution of three-dimensional elastic scattering problems by a bounded rigid obstacle. We develop a new potential theory using a rewriting of the Somigliana integral representation formula. From these results, we generalize to linear elasticity the well-known Brakhage-Werner and Combined Field Integral Equation formulations. We use a suitable approximation of the Dirichlet-to-Neumann (DtN) map as a regularizing operator in the proposed boundary integral equations. The construction of the approximate DtN map is inspired by the On-Surface Radiation Conditions method. We prove that the associated integral equations are uniquely solvable and possess very interesting spectral properties. Promising analytical and numerical investigations, in terms of spherical harmonics, with the elastic sphere are provided.

## 1. INTRODUCTION

The paper is concerned with the preconditioning of iterative methods for the scattering problem of time-harmonic elastic waves by a three-dimensional rigid obstacle. In recent years, interest has grown considerably in developing effective numerical methods for solving these problems due to the various biomedical or industrial applications such as non-destructive testing of materials and seismic exploration.

We assume the obstacle be represented by a bounded domain  $\Omega^-$  in  $\mathbb{R}^3$ . Let  $\Omega^+$  denote the exterior domain  $\mathbb{R}^3 \setminus \overline{\Omega^-}$  and  $\mathbf{n}$  the outer unit normal vector to the boundary  $\Gamma := \partial\Omega^-$ . The Lamé parameters  $\mu$  and  $\lambda$  and the density  $\rho$  are positive constants. The propagation of time-harmonic waves in a three-dimensional isotropic and homogeneous elastic medium is governed by the Navier equation

$$(1.1a) \quad \operatorname{div} \sigma(\mathbf{u}) + \rho\omega^2 \mathbf{u} = 0,$$

where  $\omega > 0$  is the frequency. Here

$$\sigma(\mathbf{u}) = \lambda(\operatorname{div} \mathbf{u})\mathbf{I}_3 + 2\mu\boldsymbol{\varepsilon}(\mathbf{u}) \quad \text{and} \quad \boldsymbol{\varepsilon}(\mathbf{u}) = \frac{1}{2}([\nabla \mathbf{u}] + [\nabla \mathbf{u}]^\top)$$

denote the stress and strain tensors respectively. Notice that  $\mathbf{I}_3$  is the 3-by-3 identity matrix and  $[\nabla \mathbf{u}]$  is the matrix whose  $j$ -th column is the gradient of the  $j$ -th component of  $\mathbf{u}$ . The field  $\mathbf{u}$  can be decomposed into a longitudinal field  $\mathbf{u}_p$  with vanishing curl and a transverse field  $\mathbf{u}_s$ , with vanishing divergence, solutions respectively to

$$(1.1b) \quad \Delta \mathbf{u}_p + \kappa_p^2 \mathbf{u}_p = 0 \quad \text{and} \quad \operatorname{curl} \operatorname{curl} \mathbf{u}_s - \kappa_s^2 \mathbf{u}_s = 0,$$

with  $\kappa_p^2 = \rho\omega^2(\lambda + 2\mu)^{-1}$  and  $\kappa_s^2 = \rho\omega^2\mu^{-1}$ . The scattering problem is formulated as follows : Given an incident displacement wave  $\mathbf{u}^{inc}$  which is assumed to solve the Navier equation in the absence of any scatterer, find the solution  $\mathbf{u}$  to the Navier equation (1.1a) in  $\Omega^+$  which satisfies the Dirichlet boundary condition

$$(1.1c) \quad \mathbf{u} = -\mathbf{u}^{inc} \quad \text{on } \Gamma.$$

In addition the scattered displacement field  $\mathbf{u}$  has to satisfy the Kupradze radiation conditions

$$(1.1d) \quad \lim_{r \rightarrow \infty} r \left( \frac{\partial \mathbf{u}_p}{\partial r} - i\kappa_p \mathbf{u}_p \right) = 0, \quad \lim_{r \rightarrow \infty} r \left( \frac{\partial \mathbf{u}_s}{\partial r} - i\kappa_s \mathbf{u}_s \right) = 0, \quad r = |\mathbf{x}|,$$

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2000 *Mathematics Subject Classification.* 35J25, 35P25, 45A05, 47G30 , 65F08, 74B05.

*Key words and phrases.* Elastic scattering, Navier equation, Dirichlet condition, boundary integral equations, analytic preconditioning.

uniformly in all directions. For existence and uniqueness of the above boundary value problem we refer to Kupradze [30, 31].

The main difficulty for simulating such exterior boundary-value problems is related to the unboundedness of the computational domain  $\Omega^+$ . The method of boundary integral equations (BIEs) is one of the principal tools to overcome this concern (see e.g. [9, 26, 31, 30]). This approach applies the Green's function formalism to reduce equivalently the governing boundary value problem to an integral equation on the surface of the scatterer. Its efficiency has been widely demonstrated for low and middle frequencies using collocation or boundary element methods (see e.g. [9, 10]). However, solving the exterior Navier problem in the high-frequency regime remains a very challenging problem for a few reasons. The discretization of boundary integral formulations leads to fully-populated and in general, non-hermitian complex linear systems. To retain a certain level of accuracy in the high-oscillatory solution, one has to consider a sufficient number of points per wavelength (about 10 points). Moreover, the vector nature of the unknown field greatly increases the size of the scattering-matrices by comparison to the acoustic case. The solution of these large and dense linear systems are handled by Krylov-subspaces iterative solvers (e.g. GMRES [39]). To make possible the use of iterative solvers for scattering problems, two kinds of techniques have to be investigated: fast methods for the computation of matrix-vector products and preconditioners to speed up the convergence of the solver.

The Fast Multipole Method (FMM) is one of the most efficient methods used to perform matrix-vector products and accelerate the resolution of the linear system. The method has been introduced by Rokhlin *et al* (e.g. [16]) and was adapted to integral equations of wave propagation in the 90's (e.g. [15, 21, 22]). Recently, the FMM has been extended to linear elasticity by Bonnet, Chaillat and Semblat [13, 14]. The theoretical complexity of the multi-level FMM is  $\mathcal{O}(N \log N)$  per iteration both for CPU time and memory, where  $N$  is the number of degrees of freedom.

Preconditioners are prescribed to yield fast convergence independently of both mesh size and frequency. A recent class of analytic preconditioners has been derived to regularize the classical BIEs. The idea is to consider a judicious integral representation of the scattered field which naturally incorporates a regularizing operator. This operator is an approximation of the Dirichlet-to-Neumann (DtN) map, when considering Dirichlet boundary value problems. The BIEs arising from this representation are compact perturbations of the identity operator. Such integral formulations can be interpreted as generalizations of the well-known Brakhage-Werner integral equation (BW) [11] and Combined Field Integral Equation (CFIE) [25]. Several well-conditioned integral equations based on this formalism have already been proposed in acoustic and electromagnetic scattering (e.g. [3, 5, 6, 12, 19, 33, 37]). A pseudo inverse of the principal classical symbol of the single layer boundary integral operator - or equivalently the principal classical symbol of the Neumann trace of the double layer boundary integral operator - is used to approach the DtN map [7, 6, 19] in the framework of the On-Surface Radiation Condition (OSRC) methods (e.g. [29, 27, 4]). This is intuitively natural in view of the Calderón formulas and the compactness of the double layer boundary integral operator. In the acoustic case, the resulting preconditioner can be expressed analytically by a simple square-root of the form  $i\sqrt{\Delta_\Gamma + \kappa^2 \mathbf{I}}$ . More precisely, a regularization of the square-root, by considering a small complex perturbation of the exterior wavenumber  $\kappa$ , is considered instead. This allows to model the creeping waves and provides the existence and uniqueness of the solution to the BIEs for any positive real values of the frequency. Furthermore, a complex Padé-approximation of the square-root operator [35] leads to a sparse matrix involving only the mass and rigidity finite element matrices. This makes the implementation of the analytic preconditioner rather easy with a low additional computational cost.

This paper aims at extending to linear elasticity such analytic preconditioning techniques. We encounter some particular difficulties that are inherent to elasticity. First of all, the double layer boundary integral operator and its adjoint are not compact even for sufficiently smooth boundaries. This implies, according to Calderón formulas, that regularizing the standard BIEs via a pseudo inverse of the single layer boundary integral operator is not sufficient to obtain well-conditioned boundary integral equations for the Dirichlet case. The principal part of the double layer boundary integral operator or its adjoint, has also to be taken into account in the preconditioner to regularize the single layer integral operator. The expression of the preconditioner is thus more complicated than in the acoustic and electromagnetic cases. Secondly, we have to impose a regularizing effect in both longitudinal and transverse directions. Finally, the resulting preconditioner - expressed in a suitable vector function basis - is not diagonal and consists in sums and products of square-roots and their inverse and

of surface differential operators. We propose to construct a more appropriate preconditioner for a numerical purpose. To this end, we introduce a new Neumann-type trace by adding a surface differential operator to the traction trace. The corresponding Dirichlet-to-Neumann (DtN) operator, called Modified DtN, plays the role of the regularizing operator in a more suited rewriting of the Somigliana integral representation formula. The expression of the preconditioner is greatly simplified. The associated preconditioned BIEs are well posed and show very interesting spectral properties for an iterative solution. Contrary to the acoustic and electromagnetic cases, defining the Neumann-to-Dirichlet (NtD) preconditioner as the inverse of the DtN preconditioner is not sufficient to construct well-conditioned BIEs for the Neumann (or cavity) scattering problem. A more extensive analysis of the DtN and NtD maps has to be realized in the transition region corresponding to the grazing modes.

The paper is organized as follows: In Section 2, we recall several results on potential theory in linear elasticity and review the standard Brakhage-Werner-type and Combined Field Integral Equation formulations. In Section 3, we present two preconditioning techniques based on a DtN approach and a modified DtN approach for the Brakhage-Werner-type (BW) BIEs. The computation of the principal parts of the elementary boundary integral operators is described in detail. This step is the key one to obtain the approximations of the DtN and modified DtN maps. We also prove existence and uniqueness for the proposed preconditioned integral equations. Section 4 is devoted to analytical and numerical investigations of the spectral properties of the classical and preconditioned BW integral operators in the particular case of the elastic sphere. Furthermore, we study the effect of both the number of spherical harmonics and the frequency increase on the convergence behavior of GMRES. Preconditioned CFIEs are built in Section 5. We give a sketch of the numerical implementation of these novel BIEs in Section 6. Finally, we draw concluding remarks and we discuss possible research lines in Section 7.

## 2. CLASSICAL BOUNDARY INTEGRAL EQUATIONS

In a first part, we review some well-known results about traces of vector fields, and integral representations of time-harmonic elastic fields. Details can be found in [2, 18, 31, 30]. We introduce a new Neumann-type trace and develop the corresponding potential theory. In a second part, we describe the classical direct and indirect approaches usually considered to solve time-harmonic exterior elastic scattering problems.

**2.1. Traces and elastic potentials.** We assume  $\Omega^-$  be a bounded domain with a closed boundary  $\Gamma$  of class  $\mathcal{C}^2$  at least. Throughout the paper we denote by  $H^s(\Omega^-)$ ,  $H_{loc}^s(\overline{\Omega^+})$  and  $H^s(\Gamma)$  the standard (local in the case of the exterior domain) complex valued, Hilbertian Sobolev spaces of order  $s \in \mathbb{R}$  defined on  $\Omega^-$ ,  $\overline{\Omega^+}$  and  $\Gamma$  respectively (with the convention  $H^0 = L^2$ ). Spaces of vector functions will be denoted by boldface letters, thus  $\mathbf{H}^s = (H^s)^3$ . Function spaces or operators related to tangential fields are labelled by the lower index  $\mathbf{t}$  and to normal fields by the lower index  $\mathbf{n}$ . We set

$$\Delta^* \mathbf{u} := \operatorname{div} \boldsymbol{\sigma}(\mathbf{u}) = \mu \Delta \mathbf{u} + (\lambda + \mu) \nabla \operatorname{div} \mathbf{u}$$

and introduce the following energy spaces

$$\begin{aligned} \mathbf{H}^1(\Omega^-, \Delta^*) &:= \left\{ \mathbf{u} \in \mathbf{H}^1(\Omega^-) : \Delta^* \mathbf{u} \in \mathbf{L}^2(\Omega^-) \right\}, \\ \mathbf{H}_{loc}^1(\Omega^+, \Delta^*) &:= \left\{ \mathbf{u} \in \mathbf{H}_{loc}^1(\overline{\Omega^+}) : \Delta^* \mathbf{u} \in \mathbf{L}_{loc}^2(\overline{\Omega^+}) \right\}. \end{aligned}$$

**Definition 2.1.** For a vector function  $\mathbf{u} \in (\mathcal{C}^\infty(\overline{\Omega^-}))^3$  we define the interior traces :

$$\begin{aligned} \gamma_0^- \mathbf{u} &= \mathbf{u}|_\Gamma \text{ (Dirichlet trace)} \\ \gamma_1^- \mathbf{u} &= \mathbf{T} \mathbf{u} \text{ (Neumann or traction trace)} \\ \gamma_{1,\alpha}^- \mathbf{u} &= \mathbf{T} \mathbf{u} - \alpha \boldsymbol{\mathcal{M}} \mathbf{u}|_\Gamma \text{ (Neumann-type trace)}, \end{aligned}$$

where  $\mathbf{T}$  denotes the traction operator defined by

$$\mathbf{T} = 2\mu \frac{\partial}{\partial \mathbf{n}} + \lambda \mathbf{n} \operatorname{div} + \mu \mathbf{n} \times \operatorname{curl}.$$

The parameter  $\alpha$  is a real-valued constant and the surface operator  $\mathcal{M}$  is the tangential Günter derivative defined by

$$\mathcal{M} = \frac{\partial}{\partial \mathbf{n}} - \mathbf{n} \operatorname{div} + \mathbf{n} \times \operatorname{curl}.$$

The following trace maps

$$\begin{aligned} \gamma_0^- : \mathbf{H}^1(\Omega^-, \Delta^*) &\rightarrow \mathbf{H}^{\frac{1}{2}}(\Gamma) \\ \gamma_1^- : \mathbf{H}^1(\Omega^-, \Delta^*) &\rightarrow \mathbf{H}^{-\frac{1}{2}}(\Gamma) \\ \gamma_{1,\alpha}^- : \mathbf{H}^1(\Omega^-, \Delta^*) &\rightarrow \mathbf{H}^{-\frac{1}{2}}(\Gamma) \end{aligned}$$

are continuous. For  $\mathbf{u} \in \mathbf{H}_{loc}^1(\Omega^+, \Delta^*)$  we define the exterior traces  $\gamma_0^+ \mathbf{u}$ ,  $\gamma_1^+ \mathbf{u}$  and  $\gamma_{1,\alpha}^+ \mathbf{u}$  in the similar way and the same mapping properties hold true.

For two  $(3 \times 3)$  matrices  $A$  and  $B$  whose columns are denoted by  $(a_1, a_2, a_3)$  and  $(b_1, b_2, b_3)$ , respectively, we set  $A : B = a_1 \cdot b_1 + a_2 \cdot b_2 + a_3 \cdot b_3$ . The following lemma is a consequence of the Gauss divergence theorem and the identity

$$(2.1) \quad \operatorname{div}(\sigma(\mathbf{u})\mathbf{v}) = \Delta^* \mathbf{u} \cdot \mathbf{v} + \sigma(\mathbf{u}) : \varepsilon(\mathbf{v}).$$

**Lemma 2.2.** *For vector functions  $\mathbf{u}$  and  $\mathbf{v}$  in  $\mathbf{H}^1(\Omega, \Delta^*)$ , we have the first Green formula*

$$(2.2) \quad \int_{\Omega} \Delta^* \mathbf{u} \cdot \mathbf{v} \, dx = \int_{\Gamma} \mathbf{T} \mathbf{u} \cdot \mathbf{v} \, ds - \int_{\Omega} \sigma(\mathbf{u}) : \varepsilon(\mathbf{v}) \, dx,$$

where  $\sigma(\mathbf{u}) : \varepsilon(\mathbf{v}) = \lambda(\operatorname{div} \mathbf{u})(\operatorname{div} \mathbf{v}) + 2\mu \varepsilon(\mathbf{u}) : \varepsilon(\mathbf{v}) = \sigma(\mathbf{v}) : \varepsilon(\mathbf{u})$ .

We use the surface differential operators: The tangential gradient  $\nabla_{\Gamma}$ , the surface divergence  $\operatorname{div}_{\Gamma}$ , the surface scalar curl  $\operatorname{curl}_{\Gamma}$ , the tangential vector curl  $\operatorname{curl} \mathbf{u}_{\Gamma}$ , the scalar Laplace-Beltrami operator  $\Delta_{\Gamma}$  and the vector Laplace-Beltrami operator  $\Delta_{\Gamma}$ . For their definitions we refer to [36, pages 68-75]. We recall some well-known surface decompositions that are useful in the sequel for the determination of the principal part of the boundary integral operators.

**Lemma 2.3.** *For a vector function  $\mathbf{u}$  and a scalar function  $v$  both defined in the neighborhood of  $\Gamma$  and sufficiently smooth, we have the following decompositions on  $\Gamma$ :*

$$(2.3) \quad \nabla v = \nabla_{\Gamma} v + \mathbf{n} \frac{\partial v}{\partial \mathbf{n}},$$

$$(2.4) \quad \operatorname{div} \mathbf{u} = \operatorname{div}_{\Gamma}(\mathbf{n} \times (\mathbf{u} \times \mathbf{n})) + 2\mathcal{H}(\mathbf{u} \cdot \mathbf{n}) + \mathbf{n} \cdot \frac{\partial \mathbf{u}}{\partial \mathbf{n}},$$

$$(2.5) \quad \mathbf{n} \times \operatorname{curl} \mathbf{u} = \nabla_{\Gamma}(\mathbf{u} \cdot \mathbf{n}) + \mathbf{n} \times (\mathcal{R} - 2\mathcal{H} \operatorname{I}_3)(\mathbf{u} \times \mathbf{n}) + \mathbf{n} \times \left( \frac{\partial \mathbf{u}}{\partial \mathbf{n}} \times \mathbf{n} \right),$$

$$(2.6) \quad \Delta v = \Delta_{\Gamma} v + 2\mathcal{H} \frac{\partial v}{\partial \mathbf{n}} + \frac{\partial^2 v}{\partial \mathbf{n}^2},$$

where  $\mathcal{H}$  is the mean curvature and  $\mathcal{R}$  is the curvature operator.

**Remark 2.4.** *The tangential Günter derivative can be rewritten*

$$\mathcal{M} \mathbf{u} = ([\nabla_{\Gamma} \mathbf{u}] - (\operatorname{div}_{\Gamma} \mathbf{u}) \cdot \operatorname{I}_3) \mathbf{n}.$$

Notice that  $[\nabla_{\Gamma} \mathbf{u}]$  is the matrix whose the  $j$ -th column is the tangential gradient of the  $j$ -th component of  $\mathbf{u}$ .

For any complex number  $\kappa$  such that  $\operatorname{Im}(\kappa) \geq 0$ , let

$$G(\kappa, \mathbf{x} - \mathbf{y}) = \frac{e^{i\kappa|\mathbf{x}-\mathbf{y}|}}{4\pi|\mathbf{x}-\mathbf{y}|}$$

be the fundamental solution of the Helmholtz equation  $\Delta v + \kappa^2 v = 0$ . Then, the fundamental solution of the Navier equation can be written

$$\Phi(\mathbf{x}, \mathbf{y}) = \frac{1}{\rho\omega^2} \left( \operatorname{curl} \operatorname{curl}_{\mathbf{x}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \operatorname{I}_3\} - \nabla_{\mathbf{x}} \operatorname{div}_{\mathbf{x}} \{G(\kappa_p, \mathbf{x} - \mathbf{y}) \operatorname{I}_3\} \right).$$

It is a 3-by-3 matrix-valued function and we have  $\Phi(\mathbf{x}, \mathbf{y}) = \Phi(\mathbf{x}, \mathbf{y})^\top = \Phi(\mathbf{y}, \mathbf{x})$ . The single and double layer potential operators are defined by

$$(2.7) \quad \mathcal{S}\varphi = \int_{\Gamma} \Phi(\cdot, \mathbf{y})\varphi(\mathbf{y})ds(\mathbf{y}) \quad \text{and} \quad \mathcal{D}\psi = \int_{\Gamma} [\mathbf{T}_{\mathbf{y}}\Phi(\cdot, \mathbf{y})]^\top \psi(\mathbf{y})ds(\mathbf{y}),$$

where  $\mathbf{T}_{\mathbf{y}} = \mathbf{T}(\mathbf{n}(\mathbf{y}), \partial_{\mathbf{y}})$  and  $\mathbf{T}_{\mathbf{y}}\Phi(\mathbf{x}, \mathbf{y})$  is the tensor obtained by applying the traction operator  $\mathbf{T}_{\mathbf{y}}$  to each column of  $\Phi(\mathbf{x}, \mathbf{y})$ .

**Theorem 2.5.** *The potential operators  $\mathcal{S}$  and  $\mathcal{D}$  are continuous from  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$  and  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  respectively to  $\mathbf{H}^1(\Omega^-, \Delta^*) \cup \mathbf{H}_{loc}^1(\Omega^+, \Delta^*)$ . For any  $\varphi \in \mathbf{H}^{-\frac{1}{2}}(\Gamma)$  and  $\psi \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$ , the potentials  $\mathcal{S}\varphi$  and  $\mathcal{D}\psi$  solve the Navier equation (1.1a) and satisfy the Kupradze radiation conditions (1.1d).*

The Dirichlet and traction traces can be applied to  $\mathcal{S}$  and  $\mathcal{D}$  and we have

$$(2.8) \quad \gamma_0^\pm \mathcal{S} = S, \quad \gamma_1^\pm \mathcal{S} = \mp \frac{1}{2}\mathbf{I} + D', \quad \gamma_0^\pm \mathcal{D} = \pm \frac{1}{2}\mathbf{I} + D, \quad \text{and} \quad \gamma_1^\pm \mathcal{D} = N,$$

where  $\mathbf{I}$  is the identity operator and the elementary boundary integral operators  $S$ ,  $D$ ,  $D'$  and  $N$  are defined, for  $\mathbf{x} \in \Gamma$ , by

$$\begin{aligned} S\varphi(\mathbf{x}) &= \int_{\Gamma} \Phi(\mathbf{x}, \mathbf{y})\varphi(\mathbf{y})ds(\mathbf{y}), \\ D\psi(\mathbf{x}) &= \int_{\Gamma} [\mathbf{T}_{\mathbf{y}}\Phi(\mathbf{x}, \mathbf{y})]^\top \psi(\mathbf{y})ds(\mathbf{y}), \\ D'\varphi(\mathbf{x}) &= \int_{\Gamma} \mathbf{T}_{\mathbf{x}}\{\Phi(\mathbf{x}, \mathbf{y})\varphi(\mathbf{y})\}ds(\mathbf{y}), \\ N\psi(\mathbf{x}) &= \int_{\Gamma} \mathbf{T}_{\mathbf{x}}\{[\mathbf{T}_{\mathbf{y}}\Phi(\mathbf{x}, \mathbf{y})]^\top \psi(\mathbf{y})\}ds(\mathbf{y}). \end{aligned}$$

The operator  $S$  is a pseudo-differential operator of order  $-1$ , i.e it is bounded from  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$  to  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  and compact from  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$  to itself. The operators  $D$  and  $D'$  are of order 0, i.e. they have a strongly singular kernel and are bounded from  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  and  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$  to themselves, respectively. The operator  $N$  is of order  $+1$ , i.e. it has a hypersingular kernel and is bounded from  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  to  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$ .

**Theorem 2.6.** *For a solution  $\mathbf{u} \in \mathbf{H}_{loc}^1(\Omega^+, \Delta^*)$  to the Navier equation (1.1a) in  $\Omega^+$  that satisfies the Kupradze radiation conditions, one can derive the Somigliana integral representation formula for  $\mathbf{x} \in \Omega^+$ :*

$$(2.9) \quad \mathbf{u}(\mathbf{x}) = \mathcal{D}\gamma_0^+ \mathbf{u}(\mathbf{x}) - \mathcal{S}\gamma_1^+ \mathbf{u}(\mathbf{x}).$$

*For a solution  $\mathbf{u} \in \mathbf{H}^1(\Omega^-, \Delta^*)$  to the Navier equation (1.1a) in  $\Omega^-$ , the Somigliana integral representation formula is given for  $\mathbf{x} \in \Omega^-$  by:*

$$(2.10) \quad \mathbf{u}(\mathbf{x}) = \mathcal{S}\gamma_1^- \mathbf{u}(\mathbf{x}) - \mathcal{D}\gamma_0^- \mathbf{u}(\mathbf{x}).$$

The Calderón projectors for the time-harmonic Navier equation are

$$P^\pm = \begin{pmatrix} \pm \frac{1}{2}\mathbf{I} + D & -S \\ N & \pm \frac{1}{2}\mathbf{I} - D' \end{pmatrix}.$$

We have  $P^+ \circ P^- = P^- \circ P^+ = 0$  and thus the relations

$$(2.11) \quad \begin{aligned} SD' &= DS, \quad D'N = ND, \\ SN &= D^2 - \frac{1}{4}\mathbf{I}, \quad NS = D'^2 - \frac{1}{4}\mathbf{I}. \end{aligned}$$

Now we show that similar results remain true if we consider the Neumann-type trace  $\gamma_{1,\alpha}$  instead of the traction trace  $\gamma_1$ .

**Theorem 2.7.** We introduce the potential operator  $\mathcal{D}_\alpha$  defined as  $\mathcal{D}$  by replacing the traction operator  $\mathbf{T}$  with  $\mathbf{T} - \alpha \mathbf{M}$ . In the same way we construct the boundary integral operators  $D_\alpha$ ,  $D'_\alpha$ , and  $N_\alpha$ . We have the following results:

- (i)  $\mathcal{D}_\alpha = \mathcal{D} - \alpha \mathcal{S} \mathbf{M}$  and for any  $\boldsymbol{\psi} \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$  the potential  $\mathcal{D}_\alpha \boldsymbol{\psi} \in \mathbf{H}^1(\Omega^-, \Delta^*) \cup \mathbf{H}_{loc}^1(\Omega^+, \Delta^*)$  satisfies the Navier equation (1.1a) and the Kupradze radiation conditions (1.1d);
- (ii)  $\gamma_{1,\alpha}^\pm \mathcal{S} = \mp \frac{1}{2} \mathbf{I} + D'_\alpha$ ,  $\gamma_0^\pm \mathcal{D}_\alpha = \pm \frac{1}{2} \mathbf{I} + D_\alpha$  and  $\gamma_{1,\alpha}^\pm \mathcal{D}_\alpha = N_\alpha$ ;
- (iii)  $\mathbf{u} = \mathcal{D}_\alpha \gamma_0^+ \mathbf{u} - \mathcal{S} \gamma_{1,\alpha}^+ \mathbf{u}$  for any solution  $\mathbf{u} \in \mathbf{H}_{loc}^1(\Omega^+, \Delta^*)$  of the Navier equation (1.1a) in  $\Omega^+$  that satisfies the Kupradze radiation conditions;
- (iv)  $\mathbf{u} = \mathcal{S} \gamma_{1,\alpha}^- \mathbf{u} - \mathcal{D}_\alpha \gamma_0^- \mathbf{u}$  for any solution  $\mathbf{u} \in \mathbf{H}^1(\Omega^-, \Delta^*)$  of the Navier equation (1.1a) in  $\Omega^-$ ;
- (v)  $S N_\alpha = D_\alpha^2 - \frac{1}{4} \mathbf{I}$  and  $N_\alpha S = D_\alpha'^2 - \frac{1}{4} \mathbf{I}$ .

We have  $\mathcal{D}_0 = \mathcal{D}$ ,  $D_0 = D$ ,  $D'_0 = D$  and  $N_0 = N$ .

*Proof.* (i) The operator  $\mathcal{D}_\alpha$  applied to any vector density  $\boldsymbol{\psi}$  writes for  $\mathbf{x} \in \Omega^\pm$

$$\mathcal{D}_\alpha \boldsymbol{\psi}(\mathbf{x}) = \int_\Gamma \left[ \left( \mathbf{T}_\mathbf{y} - \alpha \mathbf{M} \right) \Phi(\mathbf{x}, \mathbf{y}) \right]^\top \boldsymbol{\psi}(\mathbf{y}) ds(\mathbf{y}).$$

Using the relation between two vector densities  $\boldsymbol{\psi}_1$ ,  $\boldsymbol{\psi}_2$  [26]

$$\int_\Gamma (\mathbf{M} \boldsymbol{\psi}_1) \cdot \boldsymbol{\psi}_2 ds = \int_\Gamma \boldsymbol{\psi}_1 \cdot (\mathbf{M} \boldsymbol{\psi}_2) ds,$$

it follows that

$$\begin{aligned} \mathcal{D}_\alpha \boldsymbol{\psi}(\mathbf{x}) &= \int_\Gamma [\mathbf{T}_\mathbf{y} \Phi(\mathbf{x}, \mathbf{y})]^\top \boldsymbol{\psi}(\mathbf{y}) ds(\mathbf{y}) - \alpha \int_\Gamma [\mathbf{M} \Phi(\mathbf{x}, \mathbf{y})]^\top \boldsymbol{\psi}(\mathbf{y}) ds(\mathbf{y}) \\ &= \int_\Gamma [\mathbf{T}_\mathbf{y} \Phi(\mathbf{x}, \mathbf{y})]^\top \boldsymbol{\psi}(\mathbf{y}) ds(\mathbf{y}) - \alpha \int_\Gamma \Phi(\mathbf{x}, \mathbf{y}) \mathbf{M} \boldsymbol{\psi}(\mathbf{y}) ds(\mathbf{y}) \\ &= \mathcal{D} \boldsymbol{\psi}(\mathbf{x}) - \alpha \mathcal{S} \mathbf{M} \boldsymbol{\psi}(\mathbf{x}). \end{aligned}$$

(ii) We decompose the traces as follows

$$\begin{aligned} \gamma_{1,\alpha}^\pm \mathcal{S} &= \gamma_1^\pm \mathcal{S} - \alpha \mathbf{M} \gamma_0^\pm \mathcal{S} \\ \gamma_0^\pm \mathcal{D}_\alpha &= \gamma_0^\pm \mathcal{D} - \alpha \gamma_0^\pm \mathcal{S} \mathbf{M} \\ \gamma_{1,\alpha}^\pm \mathcal{D}_\alpha &= \gamma_1^\pm \mathcal{D}_\alpha - \alpha \mathbf{M} \gamma_0^\pm \mathcal{D}_\alpha \end{aligned}$$

and we apply the equalities (2.8). The first two above equalities in (ii) are obvious. We develop the third one. We have

$$\begin{aligned} \gamma_{1,\alpha}^\pm \mathcal{D}_\alpha &= \gamma_1^\pm (\mathcal{D} - \alpha \mathcal{S} \mathbf{M}) - \alpha \mathbf{M} \gamma_0^\pm (\mathcal{D} - \alpha \mathcal{S} \mathbf{M}) \\ &= N - \alpha \left( \mp \frac{1}{2} \mathbf{I} + D' \right) \mathbf{M} - \alpha \mathbf{M} \left( \pm \frac{1}{2} \mathbf{I} + D \right) + \alpha^2 \mathbf{M} \mathcal{S} \mathbf{M} \\ &= N - \alpha D' \mathbf{M} - \alpha \mathbf{M} D + \alpha^2 \mathbf{M} \mathcal{S} \mathbf{M} \\ &= N_\alpha. \end{aligned}$$

(iii) To obtain the new integral representation formula we use (i) and write, for any solution  $\mathbf{u} \in \mathbf{H}_{loc}^1(\Omega^+, \Delta^*)$ ,

$$\begin{aligned} \mathcal{D}_\alpha \gamma_0^+ \mathbf{u} - \mathcal{S} \gamma_{1,\alpha}^+ \mathbf{u} &= (\mathcal{D} - \alpha \mathcal{S} \mathbf{M}) \gamma_0^+ \mathbf{u} - \mathcal{S} (\gamma_1^+ \mathbf{u} - \alpha \mathbf{M} \gamma_0^+ \mathbf{u}) \\ &= \mathcal{D} \gamma_0^+ \mathbf{u} - \mathcal{S} \gamma_1^+ \mathbf{u} \\ &= \mathbf{u}. \end{aligned}$$

The assertion (iv) is deduced in the same way.

(v) We use the above decomposition of  $N_\alpha$  in terms of  $S$ ,  $D$ ,  $D'$ ,  $N$ , and  $\mathbf{M}$ , the equalities  $D_\alpha = D - \alpha \mathcal{S} \mathbf{M}$

and  $D'_\alpha = D' - \alpha \mathbf{M}S$  and the Calderón formulas (2.11). We get

$$\begin{aligned}
SN_\alpha &= SN - \alpha SD' \mathbf{M} - \alpha S \mathbf{M}D + \alpha^2 S \mathbf{M}S \mathbf{M} \\
&= SN - \alpha DS \mathbf{M} - \alpha S \mathbf{M}D + \alpha^2 S \mathbf{M}S \mathbf{M} \\
&= -\frac{1}{4} \mathbf{I} + D^2 - \alpha DS \mathbf{M} - \alpha S \mathbf{M}D + \alpha^2 S \mathbf{M}S \mathbf{M} \\
&= -\frac{1}{4} \mathbf{I} + D_\alpha^2,
\end{aligned}$$

and finally

$$\begin{aligned}
N_\alpha S &= NS - \alpha D' \mathbf{M}S - \alpha \mathbf{M}DS + \alpha^2 \mathbf{M}S \mathbf{M}S \\
&= NS - \alpha D' \mathbf{M}S - \alpha \mathbf{M}SD' + \alpha^2 \mathbf{M}S \mathbf{M}S \\
&= -\frac{1}{4} \mathbf{I} + D'^2 - \alpha D' \mathbf{M}S - \alpha \mathbf{M}SD' + \alpha^2 \mathbf{M}S \mathbf{M}S \\
&= -\frac{1}{4} \mathbf{I} + D'_\alpha{}^2.
\end{aligned}$$

□

**2.2. The standard BW-type and combined field integral equations.** Applying the potential theory, the elastic scattering problem (1.1a)-(1.1c)-(1.1d) can be reduced, via direct and indirect approaches, to a single uniquely solvable boundary integral equation [31]. The direct formulation consists in seeking the scattered field under the form

$$(2.12) \quad \mathbf{u}(\mathbf{x}) = S\varphi(\mathbf{x}), \quad \mathbf{x} \in \Omega^+,$$

setting  $\varphi = -\gamma_1^+(\mathbf{u} + \mathbf{u}^{inc})$ . Taking the interior Dirichlet and Neumann-type traces of the right hand side of the above equality, we obtain

$$S\varphi = -\gamma_0^- \mathbf{u}^{inc} \quad \text{and} \quad \left(\frac{\mathbf{I}}{2} + D'_\alpha\right)\varphi = -\gamma_{1,\alpha}^- \mathbf{u}^{inc}, \quad \text{on } \Gamma.$$

Under certain compatibility conditions for the incident field  $\mathbf{u}^{inc}$  [26, 31, 30], these integral equations are uniquely solvable in  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$ . To avoid any compatibility conditions, an idea is to consider the CFIE

$$(2.13) \quad \left(\frac{\mathbf{I}}{2} + D'_\alpha + i\eta S\right)\varphi = -(\gamma_{1,\alpha}^+ \mathbf{u}^{inc} + i\eta \gamma_0^+ \mathbf{u}^{inc}), \quad \text{on } \Gamma,$$

where  $\eta$  is a non-zero real constant. Then, the scattered field  $\mathbf{u}$  given by (2.12) solves the Dirichlet boundary value problem (1.1a)-(1.1c)-(1.1d) provided the physical unknown  $\varphi$  is solution of the integral equation (2.13). It can be shown that the homogenous equation (2.13) has only the trivial solution  $\varphi = \mathbf{0}$ . The integral operator  $\left(\frac{\mathbf{I}}{2} + D'_\alpha + i\eta S\right)$  is not, in general, a compact perturbation of the identity operator (close to a constant). However, an integral equation of the second kind equivalent to (2.13) can be obtained using a left equivalent regularizer [28, 30, 31]. Then we can use Riesz theory to prove existence of a unique solution to (2.13).

The indirect formulations are based on the following ansatz for the integral representation of the scattered elastic field

$$(2.14) \quad \mathbf{u}(\mathbf{x}) = \mathcal{D}_\alpha \psi(\mathbf{x}) + i\eta S\psi(\mathbf{x}), \quad \mathbf{x} \in \Omega^+,$$

with  $\eta$  a non-zero real constant and  $\psi \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$  a fictitious density. Applying the exterior Dirichlet trace to (2.14) and expressing the boundary condition (1.1c), we get the BW-type integral equation

$$(2.15) \quad \left(\frac{\mathbf{I}}{2} + D_\alpha + i\eta S\right)\psi = -\gamma_0^+ \mathbf{u}^{inc}, \quad \text{on } \Gamma.$$

Existence and uniqueness can be shown by the use of a right equivalent regularizer [28, 30, 31] for the integral equations (2.15). We mention that in the special case  $\alpha = \frac{2\mu^2}{\lambda + 3\mu}$ , it can be shown that the integral equations (2.13) and (2.15) are of the second kind [24] for any positive real-valued parameter  $\eta$ .



### 3. PRECONDITIONED BW-TYPE INTEGRAL EQUATIONS

This section is devoted to the construction of well-conditioned indirect boundary integral formulations for the solution of the Dirichlet exterior problem in elasticity. We analyze two approaches: the first one by applying the analytic preconditioning technique to the classical BW integral equation, namely equation (2.15) with  $\alpha = 0$ , and the second one by applying the same preconditioning technique to the equation (2.15) with  $\alpha \neq 0$ .

**3.1. DtN approach ( $\alpha = 0$ ).** Here the field  $\mathbf{u}$  represents a solution to the rigid body problem (1.1a)-(1.1c)-(1.1d). Assume that the exact DtN map

$$\mathbf{\Lambda}^{\text{ex}} : \gamma_0^+ \mathbf{u} \in \mathbf{H}^{\frac{1}{2}}(\Gamma) \mapsto \mathbf{\Lambda}^{\text{ex}} \gamma_0^+ \mathbf{u} := \gamma_1^+ \mathbf{u} = \mathbf{T} \mathbf{u} \in \mathbf{H}^{-\frac{1}{2}}(\Gamma)$$

is known. The Somigliana integral representation (2.9) can be rewritten under this form

$$\mathbf{u}(\mathbf{x}) = \mathcal{D} \gamma_0^+ \mathbf{u}(\mathbf{x}) - S \mathbf{\Lambda}^{\text{ex}} \gamma_0^+ \mathbf{u}(\mathbf{x}), \quad \mathbf{x} \in \Omega^+.$$

Taking the Dirichlet trace, we get the integral identity on  $\Gamma$ :

$$(3.1) \quad \frac{1}{2} \mathbf{I} + D - S \mathbf{\Lambda}^{\text{ex}} = \mathbf{I}.$$

In this ideal configuration, the solution is computed directly. However, an expression of the exact DtN operator is not available for a general surface  $\Gamma$ . Instead, an approximation  $\mathbf{\Lambda}$  of  $\mathbf{\Lambda}^{\text{ex}}$  is introduced. We propose to consider the following ansatz which is inspired by the Brakhage-Werner approach

$$\mathbf{u}(\mathbf{x}) = \mathcal{D} \psi(\mathbf{x}) - S \mathbf{\Lambda} \psi(\mathbf{x}), \quad \mathbf{x} \in \Omega^+,$$

where  $\psi$  is a fictive density. The scattered field  $\mathbf{u}$  solves the Dirichlet boundary value problem if  $\psi \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$  is a solution of the integral equation

$$(3.2) \quad \left( \frac{1}{2} \mathbf{I} + D - S \mathbf{\Lambda} \right) \psi = -\gamma_0^+ \mathbf{u}^{\text{inc}}, \quad \text{on } \Gamma.$$

The key task is now to propose an efficient approximation  $\mathbf{\Lambda}$  of the exact DtN  $\mathbf{\Lambda}^{\text{ex}}$ . The following lemma [2] gives a hint for constructing  $\mathbf{\Lambda}$ .

**Lemma 3.1.** *Assume that  $\omega$  is not an eigenfrequency of the Navier equation (1.1a) then we have*

$$\mathbf{\Lambda}^{\text{ex}} = -S^{-1} \left( \frac{1}{2} \mathbf{I} - D \right) = N \left( \frac{1}{2} \mathbf{I} + D \right)^{-1}.$$

*Proof.* By the use of (3.1) and the Calderón formula (2.11). □

We choose to construct the operator  $\mathbf{\Lambda}$  as the pseudo-differential operator associated with the principal classical symbol of the operator  $\mathbf{\Lambda}^{\text{ex}}$ . From Lemma 3.1, we have to compute the principal parts of the operators  $S$  or  $N$ . Since  $D$  and  $D'$  are operators of order 0, it is necessary to take into account their principal part too, contrary to the acoustic and electromagnetic cases. This is realized in the following three lemmas.

**Lemma 3.2.** *The principal part  $P_{-1}(S)$  of the boundary integral operator  $S$  is expressed by*

$$\begin{aligned} P_{-1}(S) = \frac{i}{2\rho\omega^2} & \left[ (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \left( \kappa_s^2 \mathbf{I}_t + \nabla_\Gamma \operatorname{div}_\Gamma \mathbf{I}_t \right) - \nabla_\Gamma (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_\Gamma \mathbf{I}_t \right. \\ & \left. + \mathbf{n} (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{\frac{1}{2}} (\mathbf{n} \cdot \mathbf{I}_n) - \mathbf{n} (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \Delta_\Gamma (\mathbf{n} \cdot \mathbf{I}_n) \right], \end{aligned}$$

where  $\mathbf{I}_n = \mathbf{n} \otimes \mathbf{n}$  and  $\mathbf{I}_t = \mathbf{I} - \mathbf{I}_n$ .

*Proof.* Since  $\operatorname{curl} \operatorname{curl} = -\Delta + \nabla \operatorname{div}$ , the fundamental solution of the Navier equation can be rewritten as follows

$$\Phi(\mathbf{x}, \mathbf{y}) = \frac{1}{\rho\omega^2} \left( (-\Delta_{\mathbf{x}} + \nabla_{\mathbf{x}} \operatorname{div}_{\mathbf{x}}) \{ G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3 \} - \nabla_{\mathbf{x}} \operatorname{div}_{\mathbf{x}} \{ G(\kappa_p, \mathbf{x} - \mathbf{y}) \mathbf{I}_3 \} \right).$$

Using Lemma 2.3, we split the operator  $\nabla \operatorname{div}$  into a sum of surface differential operators acting either on tangential densities, or normal densities to  $\Gamma$ . We have

$$\begin{aligned}
\nabla \operatorname{div} &= \left( \nabla_\Gamma + \mathbf{n} \frac{\partial}{\partial \mathbf{n}} \right) \left( \operatorname{div}_\Gamma \mathbf{I}_t + 2\mathcal{H}(\mathbf{n} \cdot \mathbf{I}) + \mathbf{n} \cdot \frac{\partial}{\partial \mathbf{n}} \right) \\
&= \nabla_\Gamma \operatorname{div}_\Gamma \mathbf{I}_t + \frac{\partial^2}{\partial \mathbf{n}^2} \mathbf{I}_n + \mathbf{n} \frac{\partial}{\partial \mathbf{n}} \operatorname{div}_\Gamma + \nabla_\Gamma \left( 2\mathcal{H}(\mathbf{n} \cdot \mathbf{I}) + \mathbf{n} \cdot \frac{\partial}{\partial \mathbf{n}} \right) \\
&= \nabla_\Gamma \operatorname{div}_\Gamma \mathbf{I}_t + \left( \Delta - \Delta_\Gamma - 2\mathcal{H} \frac{\partial}{\partial \mathbf{n}} \right) \mathbf{I}_n + \mathbf{n} \frac{\partial}{\partial \mathbf{n}} \operatorname{div}_\Gamma + \nabla_\Gamma \left( 2\mathcal{H}(\mathbf{n} \cdot \mathbf{I}) + \mathbf{n} \cdot \frac{\partial}{\partial \mathbf{n}} \right) \\
&= \nabla_\Gamma \operatorname{div}_\Gamma \mathbf{I}_t + (\Delta - \Delta_\Gamma) \mathbf{I}_n - 2\mathcal{H} \frac{\partial}{\partial \mathbf{n}} \mathbf{I}_n + \mathbf{n} \frac{\partial}{\partial \mathbf{n}} \operatorname{div}_\Gamma + \nabla_\Gamma \left( 2\mathcal{H}(\mathbf{n} \cdot \mathbf{I}) + \mathbf{n} \cdot \frac{\partial}{\partial \mathbf{n}} \right),
\end{aligned}$$

and

$$-\Delta + \nabla \operatorname{div} = (-\Delta + \nabla_\Gamma \operatorname{div}_\Gamma) \mathbf{I}_t - \Delta_\Gamma \mathbf{I}_n - 2\mathcal{H} \frac{\partial}{\partial \mathbf{n}} \mathbf{I}_n + \mathbf{n} \frac{\partial}{\partial \mathbf{n}} \operatorname{div}_\Gamma + \nabla_\Gamma \left( 2\mathcal{H}(\mathbf{n} \cdot \mathbf{I}) + \mathbf{n} \cdot \frac{\partial}{\partial \mathbf{n}} \right).$$

We use the following result [6].

**Proposition 3.3.** *The single layer boundary integral operator associated with the scalar Helmholtz equation with the wavenumber  $\kappa$  is a compact perturbation of the operator  $\frac{i}{2}(\Delta_\Gamma + \kappa^2 \mathbf{I})^{-\frac{1}{2}}$ .*

To determine  $P_{-1}(S)$ , we first apply the above surface decomposition of  $(-\Delta + \nabla \operatorname{div})$  to the single layer boundary integral operator associated with the vector Helmholtz equation with the wavenumber  $\kappa_s$ . Using Proposition 3.3 together with some well-known mapping properties of the single layer potential and its derivatives, we obtain the following top-order part

$$\frac{i}{2}(\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \left( \kappa_s^2 \mathbf{I}_t + \nabla_\Gamma \operatorname{div}_\Gamma \mathbf{I}_t \right) - \frac{i}{2} \mathbf{n} (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \Delta_\Gamma (\mathbf{n} \cdot \mathbf{I}_n).$$

Secondly, we apply the above surface decomposition of  $\nabla \operatorname{div}$  to the single layer boundary integral operator associated with the vector Helmholtz equation with the wavenumber  $\kappa_p$ . We get the top-order part

$$\frac{i}{2} \nabla_\Gamma (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_\Gamma \mathbf{I}_t - \frac{i}{2} \mathbf{n} (\kappa_p^2 \mathbf{I} + \Delta_\Gamma)^{\frac{1}{2}} (\mathbf{n} \cdot \mathbf{I}_n).$$

To conclude we subtract the two operators and multiply the result by  $(\rho\omega^2)^{-1}$ .  $\square$

**Lemma 3.4.** *The principal parts  $P_0(D)$  and  $P_0(D')$  of the boundary integral operators  $D$  and  $D'$  are given respectively by the following formulas*

$$P_0(D) = 2\mu P_{-1}(S) \mathcal{M}_p + \frac{i}{2} \left( \mathbf{n} (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_\Gamma \mathbf{I}_t - \nabla_\Gamma (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n \right),$$

and

$$P_0(D') = 2\mu \mathcal{M}_p P_{-1}(S) + \frac{i}{2} \left( \mathbf{n} (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_\Gamma \mathbf{I}_t - \nabla_\Gamma (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n \right),$$

where  $\mathcal{M}_p$  is the principal part of the operator  $\mathcal{M}$  given by

$$\mathcal{M}_p = \nabla_\Gamma (\mathbf{n} \cdot \mathbf{I}_n) - \mathbf{n} \operatorname{div}_\Gamma \mathbf{I}_t.$$

*Proof.* We consider integral representations of the operators  $D$  and  $D'$  obtained in [32]

$$\begin{aligned}
(D\psi)(\mathbf{x}) &= 2\mu S \mathcal{M} \psi(\mathbf{x}) - \int_\Gamma [\mathbf{n}(\mathbf{y}) \times \operatorname{curl}_{\mathbf{y}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}]^\top \psi(\mathbf{y}) ds(\mathbf{y}) \\
&\quad - \int_\Gamma \nabla_{\mathbf{x}} G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) ds(\mathbf{y}), \quad \mathbf{x} \in \Gamma,
\end{aligned}
\tag{3.3}$$

and

$$\begin{aligned}
(D'\varphi)(\mathbf{x}) &= 2\mu \mathcal{M} S \varphi(\mathbf{x}) - \int_\Gamma \mathbf{n}(\mathbf{x}) \times \operatorname{curl}_{\mathbf{x}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \varphi(\mathbf{y})\} ds(\mathbf{y}) \\
&\quad - \mathbf{n}(\mathbf{x}) \int_\Gamma \varphi(\mathbf{y}) \cdot \nabla_{\mathbf{y}} G(\kappa_p, \mathbf{x} - \mathbf{y}) ds(\mathbf{y}), \quad \mathbf{x} \in \Gamma.
\end{aligned}
\tag{3.4}$$

Let us work first on the operator  $D$ . The principal part of  $2\mu S\mathcal{M}$  is  $2\mu P_{-1}(S)\mathcal{M}_P$ . In view of (2.5), the top-order term of the second term in the right hand side (with the minus sign) of (3.3) is

$$-\int_{\Gamma} [\nabla_{\Gamma}^y \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{n}(\mathbf{y})\}]^{\top} (\mathbf{I}_t \psi)(\mathbf{y}) ds(\mathbf{y}) = \int_{\Gamma} \mathbf{n}(\mathbf{y}) G(\kappa_s, \mathbf{x} - \mathbf{y}) \operatorname{div}_{\Gamma} \mathbf{I}_t \psi(\mathbf{y}) ds(\mathbf{y}).$$

By composition, the principal part of the above expression is  $\frac{i}{2} \mathbf{n} (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_{\Gamma} \mathbf{I}_t$ . Furthermore, we deduce from (2.3) that the top-order term of the third term in the right hand side (with the minus sign) of (3.3) is

$$-\int_{\Gamma} \nabla_{\Gamma}^x G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) ds(\mathbf{y}) = -\nabla_{\Gamma} \int_{\Gamma} G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) ds(\mathbf{y}).$$

By composition, the principal part of the above expression is  $-\frac{i}{2} \nabla_{\Gamma} (\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n$ . Adding the three terms we obtain the principal part of  $P_0(D)$ .

Let us consider now the operator  $D'$ . The principal part of  $2\mu \mathcal{M}S$  is obviously  $2\mu \mathcal{M}_P P_{-1}(S)$ . Using (2.5), the top-order term of the second term in the right hand side (with the minus sign) of (3.4) is expressed by

$$-\int_{\Gamma} \nabla_{\Gamma}^x \{G(\kappa_s, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{x}) \cdot \varphi(\mathbf{y}))\} ds(\mathbf{y}) = -\nabla_{\Gamma} \int_{\Gamma} G(\kappa_s, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{x}) \cdot \varphi(\mathbf{y})) ds(\mathbf{y}).$$

By composition, the principal part of the above expression is  $-\frac{i}{2} \nabla_{\Gamma} (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n$ . The top-order term of the third term in the right hand side (with the minus sign) of (3.4) is (see (2.3))

$$-\mathbf{n}(\mathbf{x}) \int_{\Gamma} (\mathbf{I}_t \varphi)(\mathbf{y}) \cdot \nabla_{\Gamma}^y G(\kappa_p, \mathbf{x} - \mathbf{y}) ds(\mathbf{y}) = \mathbf{n}(\mathbf{x}) \int_{\Gamma} G(\kappa_p, \mathbf{x} - \mathbf{y}) \operatorname{div}_{\Gamma} \mathbf{I}_t \varphi(\mathbf{y}) ds(\mathbf{y}).$$

By composition, its principal part is  $\frac{i}{2} \mathbf{n} (\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_{\Gamma} \mathbf{I}_t$ . The principal part  $P_0(D')$  of  $D'$  is given by adding these three terms.  $\square$

**Lemma 3.5.** *The principal part  $P_1(N)$  of the boundary integral operator  $N$  is expressed by*

$$\begin{aligned} P_1(N) = & 2\mu P_0(D') \mathcal{M}_P + i\mu \mathcal{M}_P \left( \mathbf{n} (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_{\Gamma} \mathbf{I}_t - \nabla_{\Gamma} (\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n \right) \\ & + \frac{i}{2} \left[ (\lambda + 2\mu) \kappa_p^2 \mathbf{n} (\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n + \mu (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} (\kappa_s^2 \mathbf{I}_t - \operatorname{curl}_{\Gamma} \operatorname{curl}_{\Gamma}) \right]. \end{aligned}$$

*Proof.* We use the following integral representation of the operator  $N$

$$\begin{aligned} (N\psi)(\mathbf{x}) = & 2\mu D' \mathcal{M} \psi(\mathbf{x}) - \int_{\Gamma} \mathbf{T}_{\mathbf{x}} [\mathbf{n}(\mathbf{y}) \times \operatorname{curl}_{\mathbf{y}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}]^{\top} \psi(\mathbf{y}) ds(\mathbf{y}) \\ (3.5) \quad & - \int_{\Gamma} \mathbf{T}_{\mathbf{x}} \nabla_{\mathbf{x}} G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) ds(\mathbf{y}), \end{aligned}$$

which is obtained by applying  $\mathbf{T}_{\mathbf{x}}$  to the kernels of the right hand side in (3.3).

The principal part of  $2\mu D' \mathcal{M}$  is  $2\mu P_0(D') \mathcal{M}_P$ . To recover the principal parts of the other terms in the operator  $N$ , we consider the following form for the operator  $\mathbf{T}_{\mathbf{x}}$  [32].

$$\mathbf{T}_{\mathbf{x}} = 2\mu \mathcal{M}_{\mathbf{x}} + (\lambda + 2\mu) \mathbf{n}(\mathbf{x}) \operatorname{div}_{\mathbf{x}} - \mu \mathbf{n}(\mathbf{x}) \times \operatorname{curl}_{\mathbf{x}}.$$

We have to apply  $\mathbf{T}_{\mathbf{x}}$  to these two terms

$$(3.6) \quad t_1 = - \int_{\Gamma} [\mathbf{n}(\mathbf{y}) \times \operatorname{curl}_{\mathbf{y}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}]^{\top} \psi(\mathbf{y}) ds(\mathbf{y}),$$

$$(3.7) \quad t_2 = - \int_{\Gamma} \nabla_{\mathbf{x}} G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) ds(\mathbf{y}).$$

- First, from Lemma 3.4, applying  $2\mu \mathcal{M}_{\mathbf{x}}$  to (3.6) and (3.7), we obtain the principal part

$$2\mu \frac{i}{2} \mathcal{M}_P \left( \mathbf{n} (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_{\Gamma} \mathbf{I}_t - \nabla_{\Gamma} (\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_n \right).$$

- Secondly, we observe that

$$\begin{aligned}
(3.8) \quad & [\mathbf{n}(\mathbf{y}) \times \mathbf{curl}_{\mathbf{y}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}]^\top \psi(\mathbf{y}) \\
&= [\mathbf{curl}_{\mathbf{y}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}]^\top (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y})) \\
&= -[\mathbf{curl}_{\mathbf{y}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}] (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y})) \\
&= [\mathbf{curl}_{\mathbf{x}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) \mathbf{I}_3\}] (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y})) \\
&= \mathbf{curl}_{\mathbf{x}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\}.
\end{aligned}$$

The composition of the operator  $(\lambda + 2\mu)\mathbf{n}(\mathbf{x}) \operatorname{div}_{\mathbf{x}}$  with this term vanishes since one has  $\operatorname{div} \mathbf{curl} = 0$ . Now we apply the operator  $(\lambda + 2\mu)\mathbf{n}(\mathbf{x}) \operatorname{div}_{\mathbf{x}}$  to (3.7). We have

$$\begin{aligned}
& -(\lambda + 2\mu)\mathbf{n}(\mathbf{x}) \operatorname{div}_{\mathbf{x}} \nabla_{\mathbf{x}} G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) \\
&= -(\lambda + 2\mu)\mathbf{n}(\mathbf{x}) \Delta_{\mathbf{x}} G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})) \\
&= (\lambda + 2\mu)\kappa_p^2 \mathbf{n}(\mathbf{x}) G(\kappa_p, \mathbf{x} - \mathbf{y}) (\mathbf{n}(\mathbf{y}) \cdot \psi(\mathbf{y})).
\end{aligned}$$

The principal part of the corresponding boundary integral operator is then given by

$$\frac{i}{2}(\lambda + 2\mu)\kappa_p^2 \mathbf{n}(\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_{\mathbf{n}}.$$

- Finally, we apply the operator  $\mu \mathbf{n}(\mathbf{x}) \times \mathbf{curl}_{\mathbf{x}}$  to (3.8) and we obtain

$$\begin{aligned}
(3.9) \quad & \mu \mathbf{n}(\mathbf{x}) \times \left( (-\Delta_{\mathbf{x}} + \nabla_{\mathbf{x}} \operatorname{div}_{\mathbf{x}}) \{G(\kappa_s, \mathbf{x} - \mathbf{y}) (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\} \right) \\
&= \mu \kappa_s^2 \mathbf{n}(\mathbf{x}) \times \{G(\kappa_s, \mathbf{x} - \mathbf{y}) (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\} - \mu \mathbf{curl}_{\Gamma}^{\mathbf{x}} \operatorname{div}_{\mathbf{x}} \{G(\kappa_s, \mathbf{x} - \mathbf{y}) (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\} \\
&= \mu \kappa_s^2 \mathbf{n}(\mathbf{x}) \times \{G(\kappa_s, \mathbf{x} - \mathbf{y}) (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\} - \mu \mathbf{curl}_{\Gamma}^{\mathbf{x}} \{-\nabla_{\Gamma}^y G(\kappa_s, \mathbf{x} - \mathbf{y}) \cdot (\psi(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\},
\end{aligned}$$

since  $\mathbf{curl}_{\mathbf{x}} \mathbf{curl}_{\mathbf{x}} = -\Delta_{\mathbf{x}} + \nabla_{\mathbf{x}} \operatorname{div}_{\mathbf{x}}$ . The following integral part formula for a scalar density  $\varphi_1$  and a tangential vector density  $\varphi_2$

$$-\int_{\Gamma} (\nabla_{\Gamma} \varphi_1) \cdot \varphi_2 \, ds = + \int_{\Gamma} \varphi_1 \operatorname{div}_{\Gamma} \varphi_2 \, ds,$$

and the identity  $\operatorname{div}_{\Gamma}(\varphi_2 \times \mathbf{n}) = \operatorname{curl}_{\Gamma} \varphi_2$  give the principal part for the boundary integral operator associated with the kernel (3.9)

$$\mu \frac{i}{2} (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \left( \kappa_s^2 \mathbf{I}_{\mathbf{t}} - \mathbf{curl}_{\Gamma} \operatorname{curl}_{\Gamma} \right).$$

The composition of the operator  $\mu \mathbf{n}(\mathbf{x}) \times \mathbf{curl}_{\mathbf{x}}$  with the term (3.7) also vanishes since  $\mathbf{curl} \nabla = 0$ .

We conclude by collecting all the results.  $\square$

**Remark 3.6.** The principal part  $P_1(N)$  can be rewritten under the form

$$\begin{aligned}
P_1(N) &= 2\mu P_0(D') \mathcal{M}_P + 2\mu \mathcal{M}_P P_0(D) - (2\mu)^2 \mathcal{M}_P P_{-1}(S) \mathcal{M}_P \\
&\quad + \frac{i}{2} \left[ (\lambda + 2\mu)\kappa_p^2 \mathbf{n}(\Delta_{\Gamma} + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_{\mathbf{n}} + \mu (\Delta_{\Gamma} + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \left( \kappa_s^2 \mathbf{I}_{\mathbf{t}} - \mathbf{curl}_{\Gamma} \operatorname{curl}_{\Gamma} \right) \right].
\end{aligned}$$

The approximate DtN is then given by

$$(3.10) \quad \mathbf{\Lambda} = -(P_{-1}(S))^{-1} \left( \frac{I}{2} - P_0(D) \right) \quad \text{or} \quad \mathbf{\Lambda} = P_1(N) \left( \frac{I}{2} + P_0(D) \right)^{-1}.$$

Square-root operators of the form  $(\Delta_{\Gamma} + \kappa^2 \mathbf{I})^{1/2}$  or  $(\Delta_{\Gamma} + \kappa^2 \mathbf{I})^{1/2}$  and their inverse appear in  $\mathbf{\Lambda}$ . Since  $\Gamma$  is a compact manifold, the scalar Laplace-Beltrami operator  $\Delta_{\Gamma}$  admits a countable increasing sequence of non-negative real eigenvalues  $(\beta_j)_{j \in \mathbb{N}}$  associated with the normalized eigenfunctions  $(Y_j)_{j \in \mathbb{N}}$  satisfying the eigenvalue problem  $-\Delta_{\Gamma} Y_j = \beta_j Y_j$  in  $L^2(\Gamma)$ . For any  $\kappa > 0$ , the scalar square-root  $(\Delta_{\Gamma} + \kappa^2 \mathbf{I})^{\frac{1}{2}}$  and its inverse are defined by

$$(3.11) \quad (\Delta_{\Gamma} + \kappa^2 \mathbf{I})^{\frac{1}{2}} = \sum_{j=1}^{\infty} (\kappa^2 - \beta_j)^{\frac{1}{2}} \langle \cdot, Y_j \rangle_{L^2} Y_j \quad \text{and} \quad (\Delta_{\Gamma} + \kappa^2 \mathbf{I})^{-\frac{1}{2}} = \sum_{j=1}^{\infty} (\kappa^2 - \beta_j)^{-\frac{1}{2}} \langle \cdot, Y_j \rangle_{L^2} Y_j.$$

For  $j \geq 1$  we have  $\beta_j \neq 0$ . Since  $\Delta_\Gamma = \operatorname{div}_\Gamma \nabla_\Gamma = -\operatorname{curl}_\Gamma \operatorname{curl}_\Gamma$ , the vectors  $\nabla_\Gamma Y_j$  and  $\operatorname{curl}_\Gamma Y_j$  are eigenvectors of the vector Laplace-Beltrami operator  $\Delta_\Gamma$  with the eigenvalue  $\beta_j$ . For  $j \geq 0$  we set  $\mathbf{y}_j^{(3)} = \mathbf{n} Y_j$  and for  $j \geq 1$  we set  $\mathbf{y}_j^{(1)} = \beta_j^{-\frac{1}{2}} \nabla_\Gamma Y_j$  and  $\mathbf{y}_j^{(2)} = \beta_j^{-\frac{1}{2}} \operatorname{curl}_\Gamma Y_j$ . The concatenation of the sequences  $(\mathbf{y}_j^{(1)})_{j \in \mathbb{N}^*}$ ,  $(\mathbf{y}_j^{(2)})_{j \in \mathbb{N}^*}$  and  $(\mathbf{y}_j^{(3)})_{j \in \mathbb{N}}$  forms an orthonormal basis of  $\mathbf{L}^2(\Gamma)$ . The vector square-root  $(\Delta_\Gamma + \kappa^2 \mathbf{I})^{\frac{1}{2}}$  and its inverse are defined for tangential fields by

$$(3.12) \quad \begin{aligned} (\Delta_\Gamma + \kappa^2 \mathbf{I})^{\frac{1}{2}} &= \sum_{k=1}^2 \sum_{j=1}^{\infty} (\kappa^2 - \beta_j)^{\frac{1}{2}} \langle \cdot, \mathbf{y}_j^{(k)} \rangle_{\mathbf{L}^2} \mathbf{y}_j^{(k)} \\ (\Delta_\Gamma + \kappa^2 \mathbf{I})^{-\frac{1}{2}} &= \sum_{k=1}^2 \sum_{j=1}^{\infty} (\kappa^2 - \beta_j)^{-\frac{1}{2}} \langle \cdot, \mathbf{y}_j^{(k)} \rangle_{\mathbf{L}^2} \mathbf{y}_j^{(k)}. \end{aligned}$$

The modes  $j$  such that  $\beta_j < \kappa_p^2$  correspond to the propagative modes while the ones given for  $\beta_j > \kappa_s^2$  are linked to evanescent waves. For elastic scattering problems, a transition region corresponding to modes such that  $\beta_j \approx \kappa_p^2$  or  $\beta_j \approx \kappa_s^2$  includes the grazing modes. The artificial singularity of the square-root operator does not yield a satisfactory representation of these modes. To approximately model this behavior, we use a regularization of  $\Lambda$  by introducing a small local damping parameter  $\varepsilon > 0$  in the transition region. More precisely, we consider the following approximations of the DtN operator

$$(3.13) \quad \Lambda_\varepsilon = -(P_{-1,\varepsilon}(S))^{-1} \left( \frac{I}{2} - P_{0,\varepsilon}(D) \right) \quad \text{or} \quad \Lambda_\varepsilon = P_{1,\varepsilon}(N) \left( \frac{I}{2} + P_{0,\varepsilon}(D) \right)^{-1}$$

where  $P_{-1,\varepsilon}(S)$ ,  $P_{0,\varepsilon}(D)$ ,  $P_{1,\varepsilon}(N)$  are defined in the same way as  $P_{-1}(S)$ ,  $P_0(D)$  and  $P_1(N)$  by replacing  $\kappa_s$  and  $\kappa_p$  respectively with  $\kappa_{s,\varepsilon}$  and  $\kappa_{p,\varepsilon}$

$$(3.14) \quad \begin{cases} \kappa_{s,\varepsilon} = \kappa_s + i\varepsilon_s, & \text{with} & \varepsilon_s = 0.4\kappa_s^{\frac{1}{3}}R^{\frac{2}{3}}, \\ \kappa_{p,\varepsilon} = \kappa_p + i\varepsilon_p, & \text{with} & \varepsilon_p = 0.4\kappa_p^{\frac{1}{3}}R^{\frac{2}{3}}, \end{cases}$$

where  $R$  is the radius of the smallest sphere containing the scatterer [7]. The generalized BW integral equation for the Dirichlet boundary condition, called DtN-preconditioned BW integral equation, is given by

$$(3.15) \quad \left( \frac{1}{2} \mathbf{I} + D - S \Lambda_\varepsilon \right) \psi = -\gamma_0^+ \mathbf{u}^{inc}, \quad \text{on } \Gamma.$$

**Remark 3.7.** We have constructed a non-local On-Surface Radiation Condition (OSRC) defined by

$$\gamma_1^+ \mathbf{u} = \Lambda_\varepsilon \gamma_0^+ \mathbf{u}, \quad \text{on } \Gamma,$$

for the exterior Dirichlet elasticity problem. This is why this preconditioning approach can be also called OSRC preconditioning.

We have the following existence and uniqueness result.

**Theorem 3.8.** The DtN-preconditioned BW integral equation (3.15) is uniquely solvable in  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  for any frequency  $\omega > 0$  and damping parameters  $\varepsilon_s > 0$  and  $\varepsilon_p > 0$ .

*Proof.* We first prove that the boundary integral operator  $(\frac{1}{2} \mathbf{I} + D - S \Lambda_\varepsilon)$  can be written under the form  $A + K$ , where  $A$  is an invertible operator and  $K$  is a compact operator from  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  to itself. To this end, we set  $\psi = \psi_0^{(3)} \mathbf{y}_0^{(3)} + \sum_{j=1}^{+\infty} (\psi_j^{(1)} \mathbf{y}_j^{(1)} + \psi_j^{(2)} \mathbf{y}_j^{(2)} + \psi_j^{(3)} \mathbf{y}_j^{(3)})$ . For  $j \in \mathbb{N}^*$ , we also set  $\psi_j = (\psi_j^{(1)}, \psi_j^{(2)}, \psi_j^{(3)})^\top$  and we introduce a family of operators  $\mathcal{L}_j$  defined by  $\mathcal{L}_j \psi_j = \psi_j^{(1)} \mathbf{y}_j^{(1)} + \psi_j^{(2)} \mathbf{y}_j^{(2)} + \psi_j^{(3)} \mathbf{y}_j^{(3)}$ . We can thus write  $\psi = \psi_0^{(3)} \mathbf{y}_0^{(3)} + \sum_{j=1}^{+\infty} \mathcal{L}_j \psi_j$ . We compute

$$\left( \frac{1}{2} \mathbf{I} + P_0(D) - P_{-1}(S) \Lambda_\varepsilon \right) \psi = \frac{1}{2} \left( \mathbf{I} + P_{-1}(S) (P_{-1,\varepsilon}(S))^{-1} \right) \psi + \left( P_0(D) - P_{-1}(S) (P_{-1,\varepsilon}(S))^{-1} P_{0,\varepsilon}(D) \right) \psi.$$

From Lemma 3.2 and the spectral expansions (3.11) and (3.12) of the square-root operators, we obtain the following spectral decomposition for the operator  $P_{-1}(S)$  :

$$P_{-1}(S)\psi = s_0^{(3,3)}\psi_0^{(3)}\mathbf{y}_0^{(3)} + \sum_{j=1}^{+\infty} \frac{i}{2\rho\omega^2}\mathcal{L}_j \begin{pmatrix} s_j^{(1,1)} & 0 & 0 \\ 0 & s_j^{(2,2)} & 0 \\ 0 & 0 & s_j^{(3,3)} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix},$$

with  $s_0^{(3,3)} = i\kappa_p[2\rho\omega^2]^{-1}$  and for  $j \geq 1$ ,  $s_j^{(1,1)} = (\kappa_s^2 - \beta_j)^{\frac{1}{2}} + \beta_j(\kappa_p^2 - \beta_j)^{-\frac{1}{2}}$ ,  $s_j^{(2,2)} = \kappa_s^2(\kappa_s^2 - \beta_j)^{-\frac{1}{2}}$  and  $s_j^{(3,3)} = (\kappa_p^2 - \beta_j)^{\frac{1}{2}} + \beta_j(\kappa_s^2 - \beta_j)^{-\frac{1}{2}}$ . From Lemma 3.4, we deduce

$$P_0(D)\psi = 2\mu P_{-1}(S)\mathcal{M}_p\psi - \sum_{j=1}^{+\infty} \frac{1}{2}\mathcal{L}_j \begin{pmatrix} 0 & 0 & \tilde{d}_j^{(1,3)} \\ 0 & 0 & 0 \\ \tilde{d}_j^{(3,1)} & 0 & 0 \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix},$$

with  $\tilde{d}_j^{(1,3)} = (-\beta_j)^{\frac{1}{2}}(\kappa_p^2 - \beta_j)^{-\frac{1}{2}}$  and  $\tilde{d}_j^{(3,1)} = (-\beta_j)^{\frac{1}{2}}(\kappa_s^2 - \beta_j)^{-\frac{1}{2}}$ . The spectral decomposition of  $P_{-1,\varepsilon}(S)$  and  $P_{0,\varepsilon}(D)$  are given by the same formulas as here above with  $\kappa_s$  and  $\kappa_p$  replaced by  $\kappa_{s,\varepsilon}$  and  $\kappa_{p,\varepsilon}$  respectively. We denote by  $s_{j,\varepsilon}$  and  $\tilde{d}_{j,\varepsilon}$  their spectral coefficients. When  $j \rightarrow \infty$  (i.e  $\beta_j \rightarrow +\infty$ ), we have

$$\begin{aligned} s_j^{(1,1)}(s_{j,\varepsilon}^{(1,1)})^{-1} &= \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} + \mathcal{O}\left(\frac{1}{\beta_j}\right), \\ s_j^{(2,2)}(s_{j,\varepsilon}^{(2,2)})^{-1} &= \frac{\kappa_s}{\kappa_{s,\varepsilon}} + \mathcal{O}\left(\frac{1}{\beta_j}\right), \\ s_j^{(3,3)}(s_{j,\varepsilon}^{(3,3)})^{-1} &= \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} + \mathcal{O}\left(\frac{1}{\beta_j}\right). \end{aligned}$$

This implies

$$P_{-1}(S)(P_{-1,\varepsilon}(S))^{-1}\psi = \frac{\kappa_p}{\kappa_{p,\varepsilon}}\psi_0^{(3)}\mathbf{y}_0^{(3)} + \sum_{j=1}^{+\infty} \mathcal{L}_j \begin{pmatrix} \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} & 0 & 0 \\ 0 & \frac{\kappa_s}{\kappa_{s,\varepsilon}} & 0 \\ 0 & 0 & \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix} + \tilde{K}_1\psi,$$

with  $\tilde{K}_1$  a compact operator of negative order. The tangential Günter derivative can be expressed in the spectral functions basis as follows

$$\mathcal{M}\mathbf{y}_j^{(1)} = -\mathcal{R}\mathbf{y}_j^{(1)} + \beta_j^{\frac{1}{2}}\mathbf{y}_j^{(3)}, \quad \mathcal{M}\mathbf{y}_j^{(2)} = -\mathcal{R}\mathbf{y}_j^{(2)} \quad \text{and} \quad \mathcal{M}\mathbf{y}_j^{(3)} = \beta_j^{\frac{1}{2}}\mathbf{y}_j^{(1)} - 2\mathcal{H}\mathbf{y}_j^{(3)}.$$

We then have

$$\mathcal{M}_p\mathbf{y}_j^{(1)} = \beta_j^{\frac{1}{2}}\mathbf{y}_j^{(3)}, \quad \mathcal{M}_p\mathbf{y}_j^{(2)} = 0 \quad \text{and} \quad \mathcal{M}_p\mathbf{y}_j^{(3)} = \beta_j^{\frac{1}{2}}\mathbf{y}_j^{(1)}.$$

From this, we deduce the following asymptotic expansions when  $j \rightarrow \infty$  (i.e  $\beta_j \rightarrow +\infty$ )

$$\begin{aligned} \frac{i\mu}{\rho\omega^2}s_j^{(1,1)}\beta_j^{\frac{1}{2}} - \frac{1}{2}\tilde{d}_j^{(1,3)} &= \frac{\kappa_p^2}{2\kappa_s^2} + \mathcal{O}\left(\frac{1}{\beta_j}\right), \\ \frac{i\mu}{\rho\omega^2}s_j^{(3,3)}\beta_j^{\frac{1}{2}} - \frac{1}{2}\tilde{d}_j^{(3,1)} &= \frac{\kappa_p^2}{2\kappa_s^2} + \mathcal{O}\left(\frac{1}{\beta_j}\right). \end{aligned}$$

And we have

$$P_0(D)\psi = \frac{1}{2}\sum_{j=1}^{+\infty} \mathcal{L}_j \begin{pmatrix} 0 & 0 & \frac{\kappa_p^2}{\kappa_s^2} \\ 0 & 0 & 0 \\ \frac{\kappa_p^2}{\kappa_s^2} & 0 & 0 \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix} + \tilde{K}_2\psi,$$

where  $\tilde{K}_2$  is a compact operator of negative order.

Finally, the integral operator  $(\frac{1}{2}\mathbf{I} + D - S\mathbf{\Lambda}_\varepsilon)$  is a compact perturbation of the operator  $A$  defined by

$$(3.16) \quad A\psi = \left(\frac{1}{2} + \frac{1}{2} \frac{\kappa_p}{\kappa_{p,\varepsilon}}\right) \psi_0^{(3)} \mathbf{y}_0^{(3)} + \frac{1}{2} \sum_{j=1}^{+\infty} \mathcal{L}_j \begin{pmatrix} 1 + \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} & 0 & \frac{\kappa_p^2}{\kappa_s^2} - \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} \frac{\kappa_{p,\varepsilon}^2}{\kappa_{s,\varepsilon}^2} \\ 0 & 1 + \frac{\kappa_s}{\kappa_{s,\varepsilon}} & 0 \\ \frac{\kappa_p^2}{\kappa_s^2} - \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} \frac{\kappa_{p,\varepsilon}^2}{\kappa_{s,\varepsilon}^2} & 0 & 1 + \frac{\kappa_s^2 + \kappa_p^2}{\kappa_{s,\varepsilon}^2 + \kappa_{p,\varepsilon}^2} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix}$$

which is invertible since the coefficients of the 3-by-3 matrices are diagonally dominant. The operator is thus a Fredholm operator of index zero and the Riesz theory yields its invertibility if the operator is injective. Therefore, it is sufficient to prove that the homogeneous equation associated with (3.15) has only the trivial solution  $\psi = \mathbf{0}$  to get the existence and uniqueness of the solution to the generalized BW integral equation. Let  $\psi \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$  be a solution to  $(\frac{1}{2}\mathbf{I} + D - S\mathbf{\Lambda}_\varepsilon)\psi = 0$ . Then, the function  $\mathbf{u}$  defined by

$$\mathbf{u}^+(x) = \mathcal{D}\psi(x) - S\mathbf{\Lambda}_\varepsilon\psi(x), \quad x \in \Omega^+,$$

solves the homogeneous exterior Dirichlet problem and  $\mathbf{u}^+ = 0$  in  $\Omega^+$ . Now we set

$$\mathbf{u}^-(x) = \mathcal{D}\psi(x) - S\mathbf{\Lambda}_\varepsilon\psi(x), \quad x \in \Omega^-.$$

Then we have  $-\gamma_0^- \mathbf{u}^- = \psi$  and  $-\gamma_1^- \mathbf{u}^- = \mathbf{\Lambda}_\varepsilon\psi$ . The first Green formula (2.2) with  $\mathbf{u} = \mathbf{u}^-$  and  $\mathbf{v} = \overline{\mathbf{u}^-}$  in the interior domain  $\Omega^-$  gives

$$(3.17) \quad \int_{\Omega} \left( \lambda |\operatorname{div} \mathbf{u}^-|^2 + 2\mu |\varepsilon(\mathbf{u}^-)|^2 \right) dx - \rho\omega^2 \int_{\Omega} |\mathbf{u}^-|^2 dx = \int_{\Gamma} \overline{\psi} \cdot \mathbf{\Lambda}_\varepsilon\psi ds.$$

The imaginary part of the above equation is

$$\operatorname{Im} \left( \int_{\Gamma} \overline{\psi} \cdot \mathbf{\Lambda}_\varepsilon\psi ds \right) = 0.$$

We have the spectral decomposition for the operator  $\mathbf{\Lambda}_\varepsilon$

$$\begin{aligned} \mathbf{\Lambda}_\varepsilon\psi &= 2\mu \mathbf{M}_p \psi + i \frac{\rho\omega^2}{\kappa_{p,\varepsilon}} \psi_0^{(3)} \mathbf{y}_0^{(3)} \\ &+ i\rho\omega^2 \sum_{j=1}^{+\infty} \mathcal{L}_j \begin{pmatrix} (s_{j,\varepsilon}^{(1,1)})^{-1} & 0 & -(s_{j,\varepsilon}^{(1,1)})^{-1} \tilde{d}_{j,\varepsilon}^{(1,3)} \\ 0 & (s_{j,\varepsilon}^{(2,2)})^{-1} & 0 \\ -(s_{j,\varepsilon}^{(3,3)})^{-1} \tilde{d}_{j,\varepsilon}^{(3,1)} & 0 & (s_{j,\varepsilon}^{(3,3)})^{-1} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix}. \end{aligned}$$

- Let  $\psi \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$ . We can write

$$\int_{\Gamma} \overline{\psi} \cdot \mathbf{M}_p \psi ds = \int_{\Gamma} \mathbf{M}_p \overline{\psi} \cdot \psi ds = \overline{\int_{\Gamma} \mathbf{M}_p \psi \cdot \overline{\psi} ds}.$$

We deduce that the integral  $\int_{\Gamma} \overline{\psi} \cdot (2\mu \mathbf{M}_p \psi) ds$  is a real number.

- For any  $a \in \mathbb{C}$ , we have  $\operatorname{Im}(ia) = \operatorname{Re}(a)$ . It follows that

$$\operatorname{Im} \left( \int_{\Gamma} \overline{\psi_0^{(3)}} \mathbf{y}_0^{(3)} \cdot \left( i \frac{\rho\omega^2}{\kappa_{p,\varepsilon}} \psi_0^{(3)} \mathbf{y}_0^{(3)} \right) ds \right) = \rho\omega^2 \operatorname{Re} \left( \frac{1}{\kappa_{p,\varepsilon}} \right) |\psi_0^{(3)}|^2,$$

and  $\operatorname{Re} \left( \frac{1}{\kappa_{p,\varepsilon}} \right) = \operatorname{Re} \left( \frac{\kappa_p - i\varepsilon_p}{|\kappa_{p,\varepsilon}|^2} \right) > 0$ .

- It remains to analyze the imaginary part of

$$\int_{\Gamma} \left( \sum_{j=1}^{\infty} \overline{\mathcal{L}_j \psi_j} \right) \cdot \left[ i\rho\omega^2 \sum_{j=1}^{+\infty} \mathcal{L}_j \begin{pmatrix} (s_{j,\varepsilon}^{(1,1)})^{-1} & 0 & -(s_{j,\varepsilon}^{(1,1)})^{-1} \tilde{d}_{j,\varepsilon}^{(1,3)} \\ 0 & (s_{j,\varepsilon}^{(2,2)})^{-1} & 0 \\ -(s_{j,\varepsilon}^{(3,3)})^{-1} \tilde{d}_{j,\varepsilon}^{(3,1)} & 0 & (s_{j,\varepsilon}^{(3,3)})^{-1} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix} \right] ds,$$

which is the real part of

$$\sum_{j=1}^{+\infty} \begin{pmatrix} \overline{\psi_j^{(1)}} & \overline{\psi_j^{(2)}} & \overline{\psi_j^{(3)}} \end{pmatrix} \begin{pmatrix} (s_{j,\varepsilon}^{(1,1)})^{-1} & 0 & -(s_{j,\varepsilon}^{(1,1)})^{-1} \tilde{d}_{j,\varepsilon}^{(1,3)} \\ 0 & (s_{j,\varepsilon}^{(2,2)})^{-1} & 0 \\ -(s_{j,\varepsilon}^{(3,3)})^{-1} \tilde{d}_{j,\varepsilon}^{(3,1)} & 0 & (s_{j,\varepsilon}^{(3,3)})^{-1} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix},$$

that we rewrite

$$\sum_{j=1}^{+\infty} (s_{j,\varepsilon}^{(2,2)})^{-1} |\psi_j^{(2)}|^2 + \sum_{j=1}^{+\infty} \begin{pmatrix} \overline{\psi_j^{(1)}} & \overline{\psi_j^{(3)}} \end{pmatrix} \begin{pmatrix} (s_{j,\varepsilon}^{(1,1)})^{-1} & -(s_{j,\varepsilon}^{(1,1)})^{-1} \tilde{d}_{j,\varepsilon}^{(1,3)} \\ -(s_{j,\varepsilon}^{(3,3)})^{-1} \tilde{d}_{j,\varepsilon}^{(3,1)} & (s_{j,\varepsilon}^{(3,3)})^{-1} \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(3)} \end{pmatrix},$$

with  $(s_{j,\varepsilon}^{(2,2)})^{-1} = \kappa_{s,\varepsilon}^{-1} (1 - \frac{\beta_j}{\kappa_{s,\varepsilon}^2})^{\frac{1}{2}}$  and  $(s_{j,\varepsilon}^{(1,1)})^{-1} \tilde{d}_{j,\varepsilon}^{(1,3)} = (s_{j,\varepsilon}^{(3,3)})^{-1} \tilde{d}_{j,\varepsilon}^{(3,1)} = \frac{(-\beta_j)^{\frac{1}{2}}}{\beta_j + (\kappa_{s,\varepsilon}^2 - \beta_j)^{\frac{1}{2}} (\kappa_{p,\varepsilon}^2 - \beta_j)^{\frac{1}{2}}}$ . We have to prove that  $\operatorname{Re}((s_{j,\varepsilon}^{(2,2)})^{-1}) > 0$  and that the real parts of the above 2-by-2 matrices are positive definite matrices, for all  $j \geq 1$ . Let us set  $(1 - \frac{\beta_j}{\kappa_{s,\varepsilon}^2})^{\frac{1}{2}} = a_s + ib_s$  with  $a_s, b_s \in \mathbb{R}$  and  $a_s \geq 0$ . Then we have  $2a_s b_s = \operatorname{Im}(1 - \frac{\beta_j}{\kappa_{s,\varepsilon}^2}) = -\operatorname{Im}(\frac{\beta_j}{\kappa_{s,\varepsilon}^2}) = \beta_j \frac{2\kappa_s \varepsilon_s}{|\kappa_{s,\varepsilon}|^4} > 0$ , and thus  $a_s > 0$ ,  $b_s > 0$  and

$$\operatorname{Re}((s_{j,\varepsilon}^{(2,2)})^{-1}) = \frac{\kappa_s a_s}{|\kappa_{s,\varepsilon}|^2} + \frac{\varepsilon_s b_s}{|\kappa_{s,\varepsilon}|^2} > 0.$$

Furthermore, the real parts of the 2-by-2 matrices are symmetric and diagonalizable. These are positive definite matrices if and only if their eigenvalues are positive real constants. This is realized if their traces and determinants are positive real constants. We have

$$\operatorname{Re}((s_{j,\varepsilon}^{(1,1)})^{-1}) = \frac{\operatorname{Re}(s_{j,\varepsilon}^{(1,1)})}{|s_{j,\varepsilon}^{(1,1)}|^2} = \frac{1}{|s_{j,\varepsilon}^{(1,1)}|^2} \left( \operatorname{Re}((\kappa_{s,\varepsilon}^2 - \beta_j)^{\frac{1}{2}}) + \beta_j \frac{\operatorname{Re}((\kappa_{p,\varepsilon}^2 - \beta_j)^{\frac{1}{2}})}{|(\kappa_{p,\varepsilon}^2 - \beta_j)^{\frac{1}{2}}|^2} \right) \geq 0.$$

Assume  $\operatorname{Re}((\kappa_{s,\varepsilon}^2 - \beta_j)^{\frac{1}{2}}) = 0$ . It follows that  $\operatorname{Im}(\kappa_{s,\varepsilon}^2 - \beta_j) = 2\kappa_s \varepsilon_s = 0$ . This leads to a contradiction with the hypothesis  $\varepsilon_s > 0$ . We deduce that  $\operatorname{Re}((\kappa_{s,\varepsilon}^2 - \beta_j)^{\frac{1}{2}}) > 0$  and  $\operatorname{Re}((\kappa_{p,\varepsilon}^2 - \beta_j)^{\frac{1}{2}}) > 0$ . We have shown  $\operatorname{Re}((s_{j,\varepsilon}^{(1,1)})^{-1}) > 0$  and with the same arguments we get  $\operatorname{Re}((s_{j,\varepsilon}^{(3,3)})^{-1}) > 0$ . The traces of the 2-by-2 matrices are thus positive real constants. From long and similar calculus, we obtain the positivity of the determinants too.

Collecting all the results we conclude that

$$\operatorname{Im} \left( \int_{\Gamma} \overline{\psi} \cdot \Lambda_{\varepsilon} \psi ds \right) = 0$$

implies  $\psi = \mathbf{0}$ . The injectivity of the BIE operator is proved.  $\square$

The proof of the previous Theorem 3.8 highlights the good spectral behavior of the DtN-preconditioned BW-type integral operator  $\frac{1}{2}\mathbf{I} + D - S\Lambda_{\varepsilon}$ . From a numerical point of view, the application of the regularizing operator  $\Lambda_{\varepsilon}$  needs the discretization of the operator  $P_{0,\varepsilon}(D)$  and of either  $P_{-1,\varepsilon}(S)$  or  $P_{1,\varepsilon}(N)$ . The expressions of these operators (see Lemmas 3.2, 3.4 and 3.5) show that the associated matrices after discretization do not enjoy interesting properties. The aim is to construct a preconditioner which is easier to implement. When we look at the definition of the operator  $P_0(D)$ , we would like to delete the term  $2\mu P_{-1}(S)\mathcal{M}_p$ . In the same way, we would like to delete the term  $R = 2\mu(P_0(D')\mathcal{M}_p + \mathcal{M}_p P_0(D)) - 4\mu^2 \mathcal{M}_p P_{-1}(S)\mathcal{M}_p$  in the definition of  $P_1(N)$  (cf. Remark 3.6) so that this operator is finally diagonal. The operator  $P_0(D) - 2\mu P_{-1}(S)\mathcal{M}_p$  is nothing else than the principal part of the integral operator  $D_{2\mu}$ , and  $P_1(N) - R$  the principal part of  $N_{2\mu}$ . These observations have motivated the following section.



**3.2. Modified DtN approach** ( $\alpha \neq 0$ ). For  $\alpha \neq 0$ , we consider the following rewriting of the Somigliana representation formula, for  $\mathbf{x} \in \Omega^+$ :

$$\begin{aligned}\mathbf{u}(\mathbf{x}) &= \mathcal{D}\gamma_0^+\mathbf{u}(\mathbf{x}) - \mathcal{S}\gamma_1^+\mathbf{u}(\mathbf{x}) \\ &= \mathcal{D}\gamma_0^+\mathbf{u}(\mathbf{x}) - \alpha\mathcal{S}\mathcal{M}\gamma_0^+\mathbf{u}(\mathbf{x}) - \mathcal{S}\gamma_1^+\mathbf{u}(\mathbf{x}) + \alpha\mathcal{S}\mathcal{M}\gamma_0^+\mathbf{u}(\mathbf{x}) \\ &= (\mathcal{D} - \alpha\mathcal{S}\mathcal{M})\gamma_0^+\mathbf{u}(\mathbf{x}) - \mathcal{S}(\mathbf{\Lambda}^{\text{ex}} - \alpha\mathcal{M})\gamma_0^+\mathbf{u}(\mathbf{x}).\end{aligned}$$

We introduce the Modified Dirichlet-to-Neumann (MDtN) map

$$\mathbf{\Lambda}_\alpha^{\text{ex}} : \gamma_0^+\mathbf{u} \in \mathbf{H}^{\frac{1}{2}}(\Gamma) \mapsto \mathbf{\Lambda}_\alpha^{\text{ex}}\gamma_0^+\mathbf{u} := \gamma_{1,\alpha}^+\mathbf{u} = (\mathbf{\Lambda}^{\text{ex}} - \alpha\mathcal{M})\mathbf{u} = (\mathbf{T} - \alpha\mathcal{M})\mathbf{u} \in \mathbf{H}^{-\frac{1}{2}}(\Gamma),$$

and we have

$$\mathbf{u}(\mathbf{x}) = \mathcal{D}_\alpha\gamma_0^+\mathbf{u}(\mathbf{x}) - \mathcal{S}\mathbf{\Lambda}_\alpha^{\text{ex}}\gamma_0^+\mathbf{u}(\mathbf{x}), \quad \mathbf{x} \in \Omega^+.$$

As previously, an approximation  $\mathbf{\Lambda}_\alpha$  of  $\mathbf{\Lambda}_\alpha^{\text{ex}}$  is introduced to construct the regularized integral equation

$$(3.18) \quad \left(\frac{1}{2}\mathbf{I} + D_\alpha - \mathcal{S}\mathbf{\Lambda}_\alpha\right)\boldsymbol{\psi} = -\gamma_0^+\mathbf{u}^{\text{inc}}, \quad \text{on } \Gamma,$$

where  $\boldsymbol{\psi}$  is a fictive density. Then the scattered field  $\mathbf{u}$  expressed by

$$(3.19) \quad \mathbf{u}(\mathbf{x}) = \mathcal{D}_\alpha\boldsymbol{\psi}(\mathbf{x}) - \mathcal{S}\mathbf{\Lambda}_\alpha\boldsymbol{\psi}(\mathbf{x}), \quad \mathbf{x} \in \Omega^+,$$

solves the Dirichlet elastic boundary value problem provided the fictive density  $\boldsymbol{\psi} \in \mathbf{H}^{\frac{1}{2}}(\Gamma)$  is solution of the integral equation (3.18).

**Lemma 3.9.** *Assume that  $\omega$  is not an eigenfrequency of the Navier equation (1.1a) then we have*

$$\mathbf{\Lambda}_\alpha^{\text{ex}} = -S^{-1}\left(\frac{1}{2}\mathbf{I} - D_\alpha\right) = N_\alpha\left(\frac{1}{2}\mathbf{I} + D_\alpha\right)^{-1}.$$

*Proof.* We have  $\mathbf{\Lambda}_\alpha^{\text{ex}} = \mathbf{\Lambda}^{\text{ex}} - \alpha\mathcal{M}$ . We use Lemma 3.1 to obtain

$$\begin{aligned}(3.20) \quad \mathbf{\Lambda}_\alpha^{\text{ex}} &= -S^{-1}\left(\frac{1}{2}\mathbf{I} - D\right) - \alpha S^{-1}\mathcal{S}\mathcal{M} \\ &= -S^{-1}\left(\frac{1}{2}\mathbf{I} - (D - \alpha\mathcal{S}\mathcal{M})\right) \\ &= -S^{-1}\left(\frac{1}{2}\mathbf{I} - D_\alpha\right).\end{aligned}$$

For the second equality we apply Theorem 2.7 (v) and it remains to prove that that  $(\frac{1}{2}\mathbf{I} - D_\alpha)$  is invertible. We distinguish two cases.

- When  $\alpha \neq 2\mu$ , from the Lemmas 3.2 and 3.4 and using the same notations as in the proof of Theorem 3.8, we obtain that  $(\frac{1}{2}\mathbf{I} - D_\alpha)$  is a compact perturbation of the invertible operator defined by

$$P_0\left(\frac{1}{2}\mathbf{I} - D_\alpha\right)\boldsymbol{\psi} = \frac{1}{2} \sum_{j=1}^{+\infty} \mathcal{L}_j \begin{pmatrix} 1 & 0 & \left(\frac{\alpha}{2\mu} - 1\right)\frac{\kappa_p^2}{\kappa_s^2} + \frac{\alpha}{2\mu} \\ 0 & 1 & 0 \\ \left(\frac{\alpha}{2\mu} - 1\right)\frac{\kappa_p^2}{\kappa_s^2} + \frac{\alpha}{2\mu} & 0 & 1 \end{pmatrix} \begin{pmatrix} \psi_j^{(1)} \\ \psi_j^{(2)} \\ \psi_j^{(3)} \end{pmatrix},$$

The operator  $(\frac{1}{2}\mathbf{I} - D_\alpha)$  is Fredholm of index zero on  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  and injective provided that  $\omega$  is not an eigenfrequency of the Navier equation. From Riesz theory, we deduce the invertibility of  $(\frac{1}{2}\mathbf{I} - D_\alpha)$  from  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  to itself.

- When  $\alpha = 2\mu$ , the operator above-written is not invertible on  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$ . From the proof of Lemma 3.5, we obtain

$$\begin{aligned}(3.21) \quad N_{2\mu}\boldsymbol{\psi}(\mathbf{x}) &= (\lambda + 2\mu)\kappa_p^2 \int_\Gamma \mathbf{n}(\mathbf{x})G(\kappa_p, \mathbf{x} - \mathbf{y})(\mathbf{n}(\mathbf{y}) \cdot \boldsymbol{\psi}(\mathbf{y}))ds(\mathbf{y}) \\ &\quad + \mu \int_\Gamma \mathbf{n}(\mathbf{x}) \times \mathbf{curl}_\mathbf{x} \mathbf{curl}_\mathbf{x} \{G(\kappa_s, \mathbf{x} - \mathbf{y})(\boldsymbol{\psi}(\mathbf{y}) \times \mathbf{n}(\mathbf{y}))\} ds(\mathbf{y}), \quad \mathbf{x} \in \Gamma.\end{aligned}$$

The frequency  $\omega$  is not an eigenfrequency for the Navier equation means that the wavenumber  $\kappa_p$  is not an eigenfrequency for the Helmholtz equation and that the wavenumber  $\kappa_s$  is not an eigenfrequency

for the Maxwell's equation. In this case, one knows that the corresponding single layer boundary integral operators are invertible. The operator  $N_{2\mu}$  being an orthogonal linear combination of the acoustic and electromagnetic single layer boundary integral operators, we deduce that it is invertible from  $H_{\mathbf{n}}^{-\frac{3}{2}}(\Gamma) \oplus \mathbf{H}_{\mathbf{t}}^{\frac{1}{2}}(\Gamma)$  to  $\mathbf{H}^{-\frac{1}{2}}(\Gamma)$ . It follows that  $(D_{2\mu}^2 - \frac{1}{4}\mathbf{I})$  is invertible from  $H_{\mathbf{n}}^{-\frac{3}{2}}(\Gamma) \oplus \mathbf{H}_{\mathbf{t}}^{\frac{1}{2}}(\Gamma)$  to  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  and so is  $(\frac{1}{2}\mathbf{I} - D_{2\mu})$  by composition.  $\square$

The observations at the end of the Section 3.1 lead us to propose the following representation of the operator  $\mathbf{\Lambda}_\alpha$

$$(3.22) \quad \mathbf{\Lambda}_\alpha = P_1(N_\alpha) \left( \frac{1}{2}\mathbf{I} + P_0(D_\alpha) \right)^{-1} = P_1(N_{2\mu}) \left( \frac{1}{2}\mathbf{I} + P_0(D_{2\mu}) \right)^{-1} + (2\mu - \alpha)\mathcal{M}_P,$$

where  $P_0(D_{2\mu})$  and  $P_1(N_{2\mu})$  are the principal parts of the integral operators  $D_{2\mu}$  and  $N_{2\mu}$  respectively. These operators are expressed by

$$\begin{aligned} P_0(D_{2\mu}) &= \frac{i}{2} \left( -\nabla_\Gamma (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_\mathbf{n} + \mathbf{n} (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \operatorname{div}_\Gamma \mathbf{I}_\mathbf{t} \right) \\ P_1(N_{2\mu}) &= \frac{i\rho\omega^2}{2} \left[ \mathbf{n} (\Delta_\Gamma + \kappa_p^2 \mathbf{I})^{-\frac{1}{2}} \mathbf{n} \cdot \mathbf{I}_\mathbf{n} + (\Delta_\Gamma + \kappa_s^2 \mathbf{I})^{-\frac{1}{2}} \left( \mathbf{I}_\mathbf{t} - \frac{1}{\kappa_s^2} \operatorname{curl}_\Gamma \operatorname{curl}_\Gamma \right) \right]. \end{aligned}$$

For the same reasons as mentioned previously we will consider instead the MDtN-preconditioner

$$(3.23) \quad \mathbf{\Lambda}_{\alpha,\varepsilon} = P_{1,\varepsilon}(N_{2\mu}) \left( \frac{I}{2} + P_{0,\varepsilon}(D_{2\mu}) \right)^{-1} + (2\mu - \alpha)\mathcal{M}_P$$

where  $P_{1,\varepsilon}(N_{2\mu})$  and  $P_{0,\varepsilon}(D_{2\mu})$  are deduced from  $P_1(N_{2\mu})$  and  $P_0(D_{2\mu})$  respectively by substituting  $\kappa_s$  and  $\kappa_p$  for  $\kappa_{s,\varepsilon}$  and  $\kappa_{p,\varepsilon}$  (see (3.14)). The new boundary integral equation for the Dirichlet boundary condition is given by

$$(3.24) \quad \left( \frac{1}{2}\mathbf{I} + D_\alpha - S\mathbf{\Lambda}_{\alpha,\varepsilon} \right) \boldsymbol{\psi} = -\gamma_0^+ \mathbf{u}^{inc}, \quad \text{on } \Gamma,$$

and is called MDtN-preconditioned BW integral equation. Following the steps of the proof of Theorem 3.8, we can prove the existence and uniqueness of the solution of (3.24).

**Theorem 3.10.** *Let  $\alpha$  a real-valued parameter. The MDtN-preconditioned BW integral equation (3.24) is uniquely solvable in  $\mathbf{H}^{\frac{1}{2}}(\Gamma)$  for any frequency  $\omega > 0$  and damping parameters  $\varepsilon_s > 0$  and  $\varepsilon_p > 0$ .*

*Proof.* The operator associated to the integral equation (3.24) is a compact perturbation of the operator associated to the integral equation (3.15). More precisely, we have

$$(3.25) \quad \left( \frac{1}{2}\mathbf{I} + D_\alpha - S\mathbf{\Lambda}_{\alpha,\varepsilon} \right) = \left( \frac{1}{2}\mathbf{I} + D - S\mathbf{\Lambda}_\varepsilon \right) - \alpha S(\mathcal{M} - \mathcal{M}_P).$$

Injectivity can be proved in the same way.  $\square$

We will study in the following section if the choice of the parameter  $\alpha$  impacts, or not, the spectral properties of the MDtN-preconditioned BW integral operator (3.24). The advantage of the MDtN-preconditioner  $\mathbf{\Lambda}_{\alpha,\varepsilon}$  is its more straightforward expression compared to the DtN-one (3.13). Its numerical implementation can be done easily using previous investigations on acoustic and electromagnetic OSRC-like preconditioners [7].

#### 4. SPECTRAL STUDY FOR THE SPHERICAL CASE

In this section, we present a numerical investigation of the eigenvalues of the standard, DtN- and MDtN-preconditioned BW integral operators for the spherical case. The use of complex Padé rational approximants to localize the MDtN-preconditioner is discussed. Furthermore, we analyze the convergence properties of the GMRES algorithm for solving the different BW-type integral equations.

**4.1. Asymptotic analysis.** Let  $\Gamma$  be the sphere of radius  $R$ . Spectral decomposition, in terms of the vector spherical harmonics, of the elementary boundary integral operators  $S$ ,  $D$  and  $N$ , and of their principal parts can be obtained (cf. Appendix Appendix). Let us denote by  $B_m^{(j,l)}$ ,  $(j,l) \in \{1,2,3\} \times \{1,2,3\}$ , the spectral coefficients of the decomposition of an integral operator  $B$  ( $B = S, D$  or  $N$ ). Each coefficient is of multiplicity  $2m+1$ . We study their asymptotic behavior. To this end, we distinguish three zones of modes: the hyperbolic zone for  $|\kappa_p R| \rightarrow +\infty$  and  $m \ll \kappa_p R$  (propagative modes), the elliptic zone when  $m \rightarrow +\infty$  and  $m \gg \kappa_s R$  (evanescent modes), and the transition zone of physical surface modes between  $m \approx \kappa_p R$  and  $m \approx \kappa_s R$ . First, let us consider the hyperbolic zone. We have the following results.

**Proposition 4.1.** *In the hyperbolic zone, that is  $|\omega R| \rightarrow +\infty$ , the following asymptotic behaviors hold:*

- for the operator  $S$  :

$$\begin{aligned} S_m^{(1,1)} &= \frac{i}{\mu \kappa_s} \left( \sin^2(\kappa_s R - (m+1)\frac{\pi}{2}) - \frac{i}{2} \sin(2(\kappa_s R - (m+1)\frac{\pi}{2})) \right) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \\ S_m^{(2,2)} &= \frac{i}{\mu \kappa_s} \left( \cos^2(\kappa_s R - (m+1)\frac{\pi}{2}) + \frac{i}{2} \sin(2(\kappa_s R - (m+1)\frac{\pi}{2})) \right) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \\ S_m^{(3,3)} &= \frac{i}{(\lambda + 2\mu)\kappa_p} \left( \sin^2(\kappa_p R - (m+1)\frac{\pi}{2}) - \frac{i}{2} \sin(2(\kappa_p R - (m+1)\frac{\pi}{2})) \right) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 0, \\ S_m^{(1,3)} &= \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \end{aligned}$$

- for the operator  $D$  :

$$\begin{aligned} D_m^{(1,1)} &= \frac{1}{2} - \sin^2(\kappa_s R - (m+1)\frac{\pi}{2}) + \frac{i}{2} \sin(2(\kappa_s R - (m+1)\frac{\pi}{2})) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \\ D_m^{(2,2)} &= \frac{1}{2} - \cos^2(\kappa_s R - (m+1)\frac{\pi}{2}) - \frac{i}{2} \sin(2(\kappa_s R - (m+1)\frac{\pi}{2})) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \\ D_m^{(3,3)} &= \frac{1}{2} - \sin^2(\kappa_p R - (m+1)\frac{\pi}{2}) + \frac{i}{2} \sin(2(\kappa_p R - (m+1)\frac{\pi}{2})) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 0, \\ D_m^{(1,3)} &= \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad D_m^{(3,1)}(\omega R) = \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \end{aligned}$$

- and for the operator  $N$  :

$$\begin{aligned} N_m^{(1,1)} &= \frac{\mu \kappa_s}{i} \left( -\cos^2(\kappa_s R - (m+1)\frac{\pi}{2}) - \frac{i}{2} \sin(2(\kappa_s R - (m+1)\frac{\pi}{2})) \right) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \\ N_m^{(2,2)} &= \frac{\mu \kappa_s}{i} \left( -\sin^2(\kappa_s R - (m+1)\frac{\pi}{2}) + \frac{i}{2} \sin(2(\kappa_s R - (m+1)\frac{\pi}{2})) \right) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1, \\ N_m^{(3,3)} &= i(\lambda + 2\mu)\kappa_p \left( \cos^2(\kappa_p R - (m+1)\frac{\pi}{2}) + \frac{i}{2} \sin(2(\kappa_p R - (m+1)\frac{\pi}{2})) \right) + \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 0, \\ N_m^{(1,3)} &= \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad N_m^{(3,1)}(\omega R) = \mathcal{O}\left(\frac{1}{|\omega R|}\right), \quad m \geq 1. \end{aligned}$$

*Proof.* We use asymptotic expansions for the spherical Bessel and Hankel functions expressed in [1]. □

In the elliptic zone, we get

**Proposition 4.2.** *In the elliptic zone, that is  $m \rightarrow +\infty$ , the following asymptotic behaviors hold :*

- for the operator  $S$  :

$$\begin{aligned} S_m^{(1,1)} &= \frac{1}{\mu} \frac{R}{2(2m+1)} + \frac{1}{(\lambda + 2\mu)} \frac{R}{2(2m+1)} + \mathcal{O}\left(\frac{1}{m^3}\right), \\ S_m^{(2,2)} &= \frac{1}{\mu} \frac{R}{2m+1} + \mathcal{O}\left(\frac{1}{m^3}\right), \\ S_m^{(3,3)} &= \frac{1}{\mu} \frac{R}{2(2m+1)} + \frac{1}{(\lambda + 2\mu)} \frac{R}{2(2m+1)} + \mathcal{O}\left(\frac{1}{m^3}\right), \\ S_m^{(1,3)} &= \mathcal{O}\left(\frac{1}{m^2}\right), \end{aligned}$$

- for the operator  $D$  :

$$\begin{aligned}
D_m^{(1,1)} &= -\frac{\mu}{\lambda + 2\mu} \frac{1}{2(2m+1)} + \mathcal{O}\left(\frac{1}{m^3}\right), \\
D_m^{(2,2)} &= -\frac{3}{2(2m+1)} + \mathcal{O}\left(\frac{1}{m^3}\right), \\
D_m^{(3,3)} &= -\frac{3\mu}{\lambda + 2\mu} \frac{1}{2(2m+1)} + \mathcal{O}\left(\frac{1}{m^3}\right), \\
D_m^{(1,3)} &= \frac{\mu}{2(\lambda + 2\mu)} + \mathcal{O}\left(\frac{1}{m^2}\right),
\end{aligned}$$

- and for the operator  $N$  :

$$\begin{aligned}
N_m^{(1,1)} &= \frac{-2\mu(\lambda + \mu)}{\lambda + 2\mu} \frac{m + \frac{1}{2}}{2R} + \mathcal{O}\left(\frac{1}{m}\right), \\
N_m^{(2,2)} &= -\mu \frac{m + \frac{1}{2}}{2R} + \mathcal{O}\left(\frac{1}{m}\right), \\
N_m^{(3,3)} &= \frac{-2\mu(\lambda + \mu)}{\lambda + 2\mu} \frac{m + \frac{1}{2}}{2R} + \mathcal{O}\left(\frac{1}{m}\right), \\
N_m^{(1,3)} &= N_m^{(3,1)} = \frac{\mu(3\lambda + \mu)}{2R(\lambda + 2\mu)} + \mathcal{O}\left(\frac{1}{m^2}\right).
\end{aligned}$$

*Proof.* We use asymptotic expansions given in [1] or lemmas 3.2-3.5 . □

Let us validate both these asymptotic estimates and the principal parts of the elementary boundary integral operators proposed in Section 3.1. We keep only the modes  $m$  such that  $|m| \leq m_{\max}$  with  $m_{\max} = [4\kappa_s]$  (cf. Section 4.2). The value  $[x]$  denotes the integer part of a real number  $x$ . We set the physical parameters  $\kappa_s = 16\pi$ ,  $\rho = \mu = 1$ , and  $\lambda = 2$ . This corresponds to the Poisson's ratio  $\nu = 1/3$ , and to the relation  $\kappa_s = 2\kappa_p$ . We can see in Fig. 1 that the estimates obtained in the elliptic zone (cf. Proposition 4.2) well predict the behavior of the compact operator  $S$ . The principal part of the operator  $S$  is given by the diagonal coefficients. The operator  $S$  and the proposed operator  $P_{-1,\varepsilon}(S)$  exhibit the same asymptotic behavior in the elliptic zone. Furthermore, their spectral coefficients have the same magnitude order in the hyperbolic and transition parts. We conclude that the operator  $P_{-1,\varepsilon}(S)$  is a good approximation of the boundary integral operator  $S$ . We report in Fig. 2 numerical comparisons for the integral operator  $D$ . Same conclusions hold. Here, the principal part of the operator  $D$  is represented by the extra-diagonal coefficients. The derived estimates in the elliptic zone are validated and the operator  $P_{0,\varepsilon}(D)$  contains the necessary spectral informations on the operator  $D$ . Fig. 3 shows results on the integral operator  $N$ . The operator  $N$  is a first-order pseudodifferential operator. The linear dependance of the diagonal coefficients on  $m$  in the elliptic zone indicates this property. The operator  $P_{1,\varepsilon}(N)$  has an identical behavior.

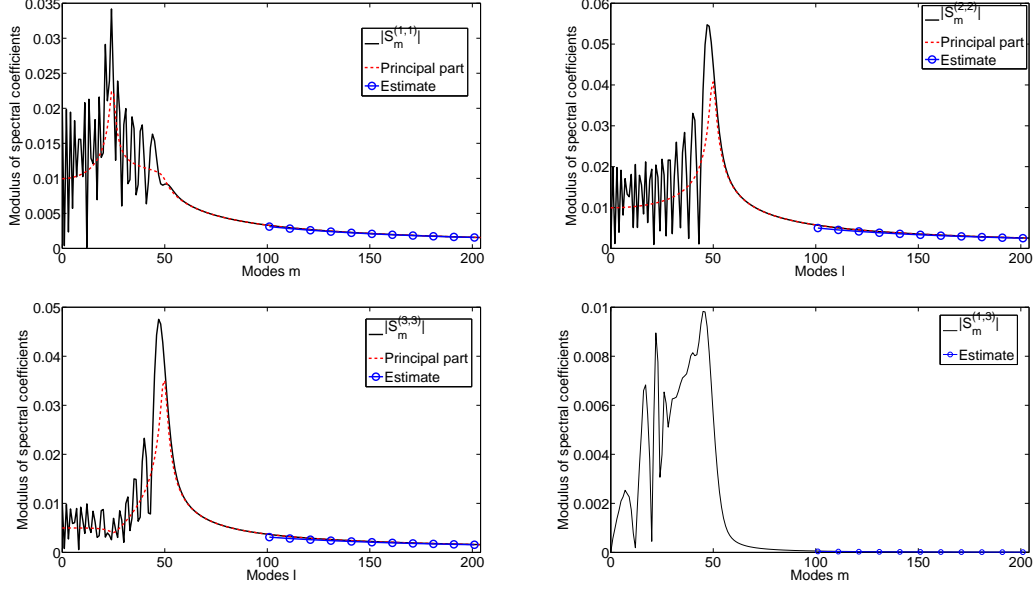


FIGURE 1. Asymptotic behavior: comparison between the integral operator  $S$  and the principal part  $P_{-1,\varepsilon}(S)$ , for  $\kappa_s = 16\pi$  and  $m_{\max} = [4\kappa_s]$ .

We focus now on the principal parts  $P_{0,\varepsilon}(D_{2\mu})$  and  $P_{1,\varepsilon}(N_{2\mu})$  that appear in the definition of the MDtN-preconditioner. We can obtain a spectral decomposition of the integral operators  $D_{2\mu}$  and  $N_{2\mu}$ , and of their principal parts  $P_{0,\varepsilon}(D_{2\mu})$  and  $P_{1,\varepsilon}(N_{2\mu})$  in the same way than in Appendix Appendix. The proposed principal parts are good approximations to the integral operators  $D_{2\mu}$  and  $N_{2\mu}$  (see Fig. 4 and 5). The spectral extra-diagonal coefficients of  $N_{2\mu}$  and  $P_{1,\varepsilon}(N_{2\mu})$  are equal to zero for any mode.

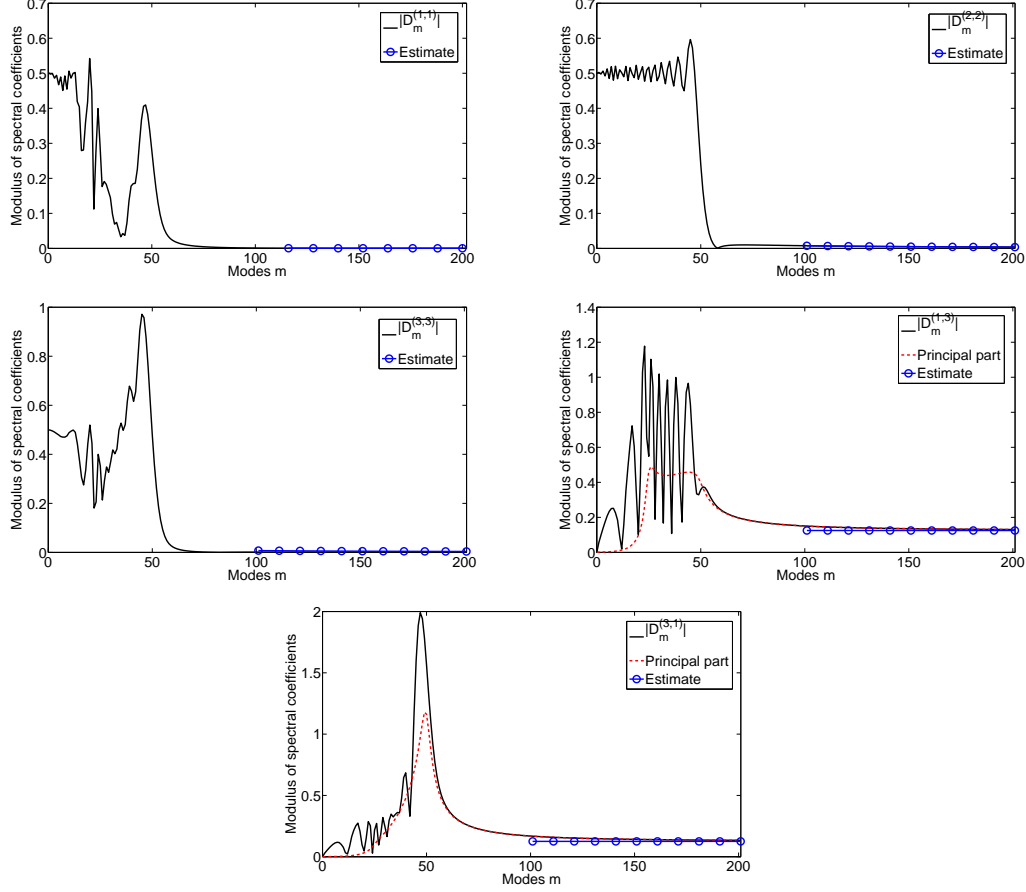


FIGURE 2. Asymptotic behavior: comparison between the integral operator  $D$  and the principal part  $P_{0,\epsilon}(D)$ , for  $\kappa_s = 16\pi$  and  $m_{\max} = \lfloor 4\kappa_s \rfloor$ .

**4.2. Spectral comparison of standard and preconditioned BW-type integral formulations.** We consider the unit sphere as the scatterer. In all our simulations, the mechanical parameters are chosen such that the wavenumbers satisfy  $\kappa_s = 2\kappa_p$ . They are given by  $\rho = 1$ ,  $\nu = 1/3$ ,  $\mu = 1$  and  $\lambda = 2$ . This subsection is devoted to analyze the effect of the preconditioning on the eigenvalue clustering of the BW-type integral operators. In a finite dimensional approximation, we keep only the modes  $m$  such that  $m \leq m_{\max}$ . The number of modes  $m_{\max}$  to retain must be large enough to capture the hyperbolic and transition parts of the spectrum ( $m_{\max} \geq \kappa_p$ ) but also the elliptic part ( $m_{\max} \geq \kappa_s$ ), while avoiding the divergence of the spherical Bessel and Hankel functions. For our simulations, we will always set  $\kappa_s + 7.5\log_{10}(\kappa_s + \pi) \leq m_{\max} \leq \lfloor 4\kappa_s \rfloor$ . The lower bound is proposed in the context of multipole methods [14]. This truncation parameter  $m_{\max}$  represents the mesh refinement.

First, we numerically exhibit an optimal parameter  $\eta_{\text{opt}}$  which minimizes the condition number of the usual BW integral operator (2.15) with  $\alpha = 0$ . A judicious choice is around the value  $\eta_{\text{opt}} = (\kappa_s + \kappa_p)/2$ . We illustrate this observation in Fig. 6. We will consider this value in the sequel, and (2.15) with this choice is the reference integral equation.

Secondly, we study how the parameter  $\alpha$  influences the eigenvalue clustering of the MDtN-preconditioned BW integral operator (3.23). We report on Fig. 7-left the distribution of the eigenvalues for different values of  $\alpha$ . The case  $\alpha = 0$  corresponds to the DtN-preconditioned BW integral operator (3.15). We denote by  $\alpha_{HH} := 2\mu^2/(\lambda + 3\mu) = 0.4$  the parameter considered by Hähner and Hsiao in [24]. The spectral properties of the MDtN-preconditioned BW integral operator are sensibly the same when  $|\alpha| \leq 2\mu$ . The eigenvalues are particularly well clustered around the point  $(1, 0)$  for these values (see Fig. 7-left), and by consequence

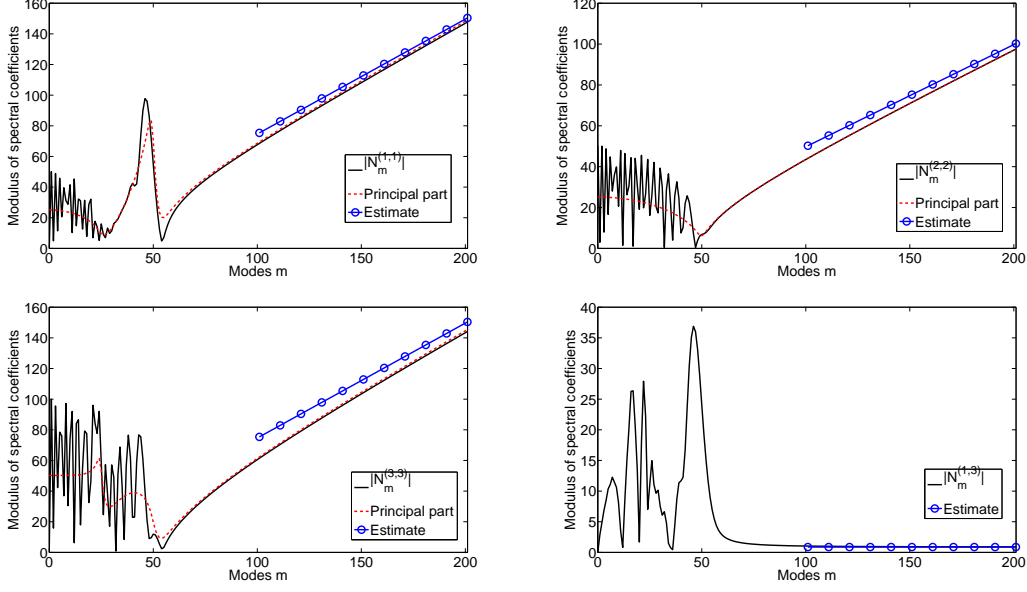


FIGURE 3. Asymptotic behavior: comparison between the integral operator  $N$  and the principal part  $P_{1,\epsilon}(N)$ , for  $\kappa_s = 16\pi$  and  $m_{\max} = [4\kappa_s]$ .

the condition number of the MDtN-preconditioned BW integral operator is close to 1 (see Fig. 7-right). A good compromise between an interesting eigenvalue clustering and an optimal computational cost is to consider  $\alpha = 2\mu$  in (3.23), even if the implementation of the surfacic differential operator  $\mathcal{M}_p$  is easy and not very expensive. In all the following tests, we set  $\alpha = 2\mu$  (unless indicated otherwise).

The MDtN-preconditioner  $\Lambda_{2\mu,\epsilon}$  (cf. (3.23)) is defined with the help of non-local inverse square-root operators. We use complex Padé approximants with a rotating branch-cut technique [8, 34, 35, 7] to a suitable localization of these operators. We will discuss this point in Section 6. We compare the analytical eigenvalues of the MDtN-preconditioned BW integral operator obtained with the exact square-root operators, and the ones obtained considering Padé approximants. Efficiency of Padé approximants depends on two parameters to choose: their order  $(2L + 1)$  and the  $\theta$ -rotation of the branch-cut. We consider  $\theta = \pi/2$ . We study how the order impacts on the clustering of the eigenvalues. To this aim, we consider different Padé orders in Fig. 8. The clustering of the eigenvalues around the point  $(1, 0)$  is better with higher Padé orders. We can see a spiral curve which is absorbed by the accumulation point when the Padé order increases. Complex Padé rational approximants for  $L \geq 10$  provide an adequate tool to localize the MDtN-preconditioner  $\Lambda_{2\mu,\epsilon}$  (cf. Fig. 10 a)). From now, we set  $(\theta, L) = (\pi/2, 12)$ .

Finally, we compare the spectral behavior of different integral equations: the BW-type IEs (2.15) with  $(\alpha, \eta) = (0, \eta_{\text{opt}})$  and  $(\alpha, \eta) = (\alpha_{HH}, \eta_{\text{opt}})$  called standard BW and BW-HH respectively, the DtN- and MDtN-preconditioned BW IE (3.15) and (3.24). We also consider the IE (3.2) with a DtN approximation proposed by Gächter and Grote in [23], called GGDtN approach. This approximation is constructed in the framework of non-reflecting boundary conditions for the spherical case. In Fig. 9, we compare the analytic eigenvalues of the different BW-type integral operators. The standard BW IEs show a similar behavior with more clustered eigenvalues around an accumulation point for the BW-HH one according to its second-kind type [24]. The GGDtN approach does not allow a better eigenvalue distribution than the reference BW IE. The approximation proposed in [23] considers efficiently the hyperbolic part of the exact DtN operator but this information is not sufficient to regularize the usual BW IE. All the modes have to be taken account in the preconditioner. This is done by considering the MDtN-preconditioner (3.23). The efficient regularizing effect of such an analytic preconditioning technique is illustrated here. This is confirmed when we observe the behavior of the condition number (cf. Fig. 10). The condition number of the MDtN-preconditioned BW IE remains between 1.25 and 1.67 independently of the wavenumber  $\kappa_s$  (and hence  $\kappa_p$  too). As predicted by the distribution of the eigenvalues

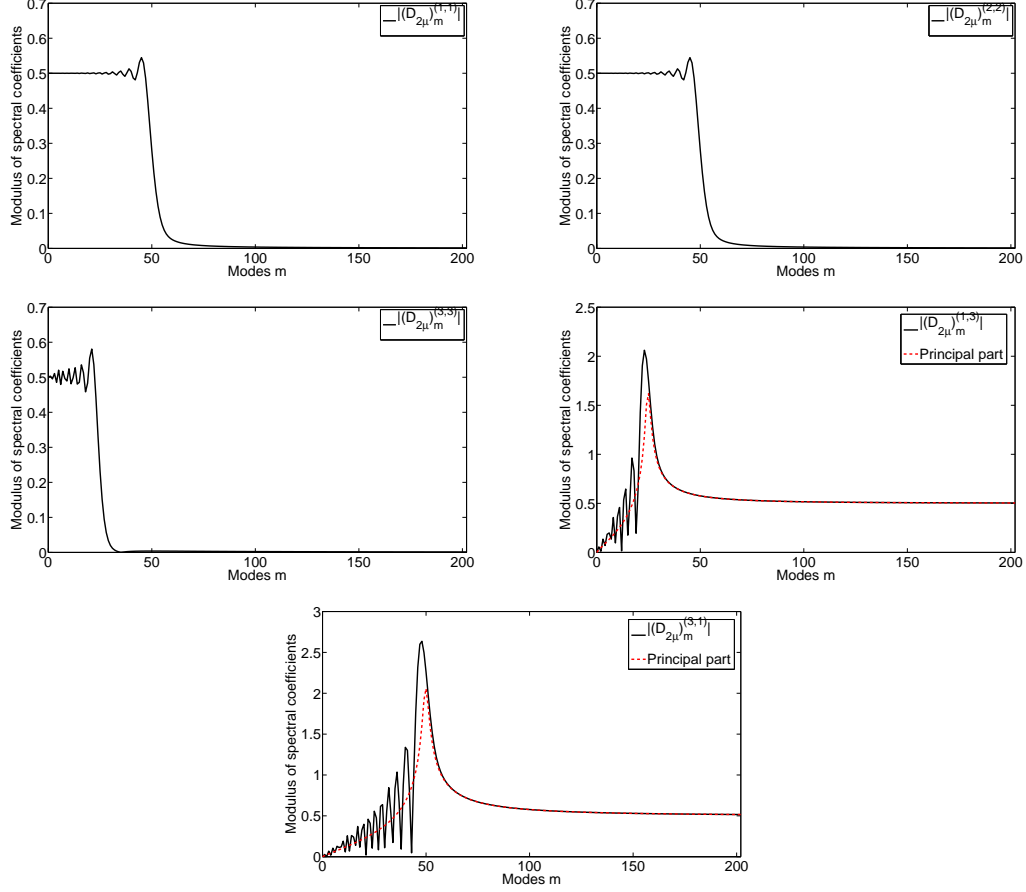


FIGURE 4. Asymptotic behavior: comparison between the integral operator  $D_{2\mu}$  and the principal part  $P_{0,\varepsilon}(D_{2\mu})$ , for  $\kappa_s = 16\pi$  and  $m_{\max} = [4\kappa_s]$ .

(cf. Fig 7-left), the parameters  $\alpha = 0$ ,  $\alpha = \alpha_{HH}$  and  $\alpha = 2\mu$  lead to same good results. This is not the case for the BW-type IEs. The dependance on the frequency comes from the largest magnitude eigenvalues linked to a grazing mode. The condition number of the standard BW IEs is independent on the truncation parameter  $m_{\max}$  according the asymptotic behavior of the eigenvalues in the elliptic part. The MDtN-preconditioned EIs preserve this interesting property.

**4.3. Convergence of the iterative solver GMRES.** We study the scattering by the unit sphere of an incident plane elastic wave of polarization  $\mathbf{p}$  and propagating in the direction  $\mathbf{d}$ . Here, we consider shear plane waves. In this case, the polarization of the plane waves is orthogonal to the direction of propagation. We fix  $\mathbf{p} = (1, 0, 0)^T$  and  $\mathbf{d} = (0, 0, 1)^T$ .

We use the iterative method GMRES with no restart for solving the linear systems of the standard and MDtN-preconditioned BW IEs. The solution of the linear systems is expanded on the basis of normal and tangential vector spherical harmonics (see [32] for the coefficients of the incident wave). The size of the considered matrices is  $N = (3(2m_{\max} + 1)^2 - 2)$ . The GMRES iterations are stopped when the initial residual has decreased by a factor of  $10^{-5}$ . We examine the influence of an increase of the frequency and of the truncation parameter  $m_{\max}$  on the GMRES convergence. In Fig. 11-left, the value of the wavenumber  $\kappa_s$  varies from  $\pi$  to  $8\pi$ . The number of GMRES iterations increases with  $\kappa_s$  for the classical BW integral equation. The MDtN preconditioning leads to an independence of the GMRES convergence on  $\kappa_s$ , even for high values of  $\kappa_s$ . Only 7 iterations are required



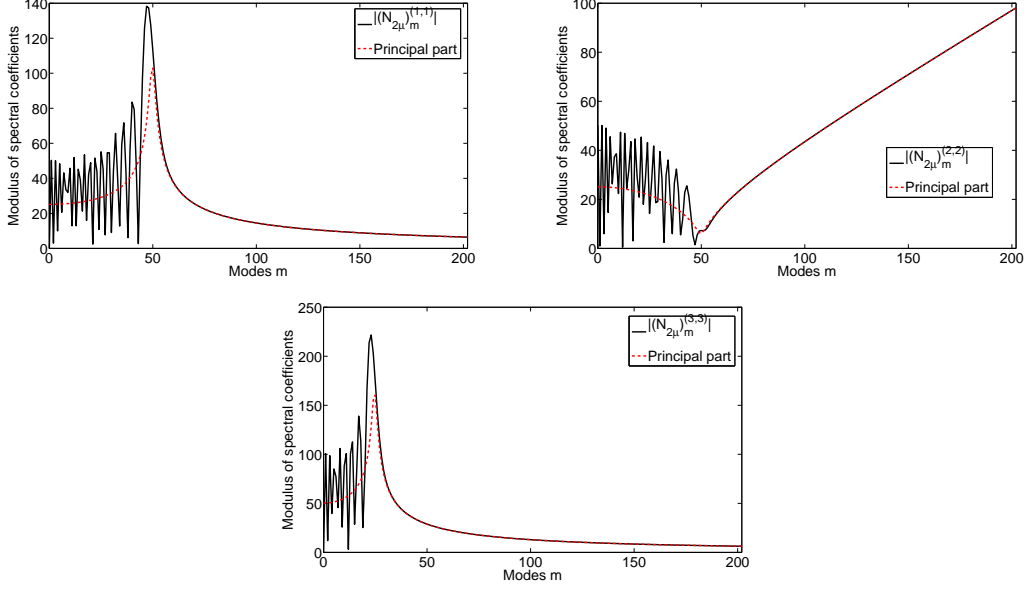


FIGURE 5. Asymptotic behavior: comparison between the integral operator  $N_{2\mu}$  and the principal part  $P_{1,\varepsilon}(N_{2\mu})$ , for  $\kappa_s = 16\pi$  and  $m_{\max} = [4\kappa_s]$ .

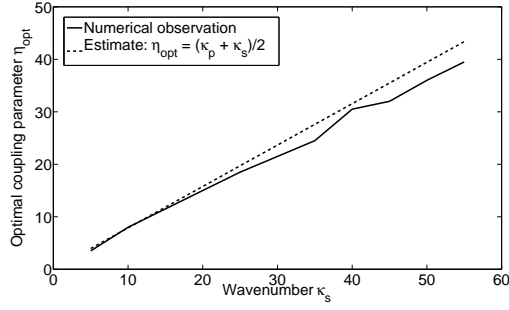


FIGURE 6. Optimal coupling parameter  $\eta_{\text{opt}}$  for the classical BW integral operator versus  $\kappa_s$ , taking  $\kappa_s = 2\kappa_p$  and  $m_{\max} = [4\kappa_s]$ .

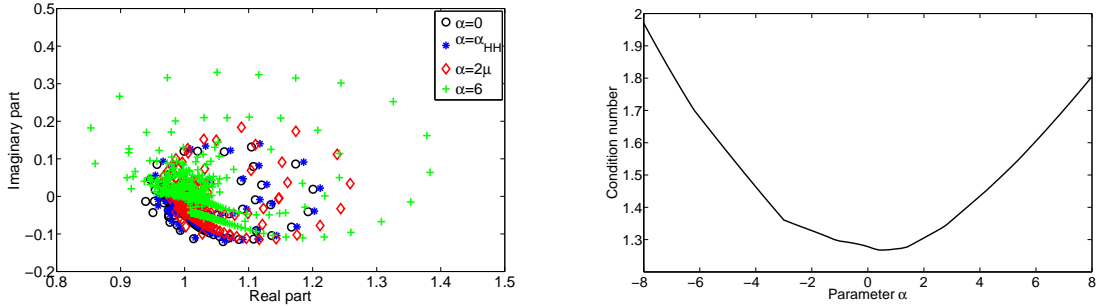


FIGURE 7. Distribution of the eigenvalues (left) and condition number (right) of the MDtN-preconditioned BW integral operator according to  $\alpha$  ( $\kappa_s = 32\pi$  and  $m_{\max} = [3\kappa_s]$ ).

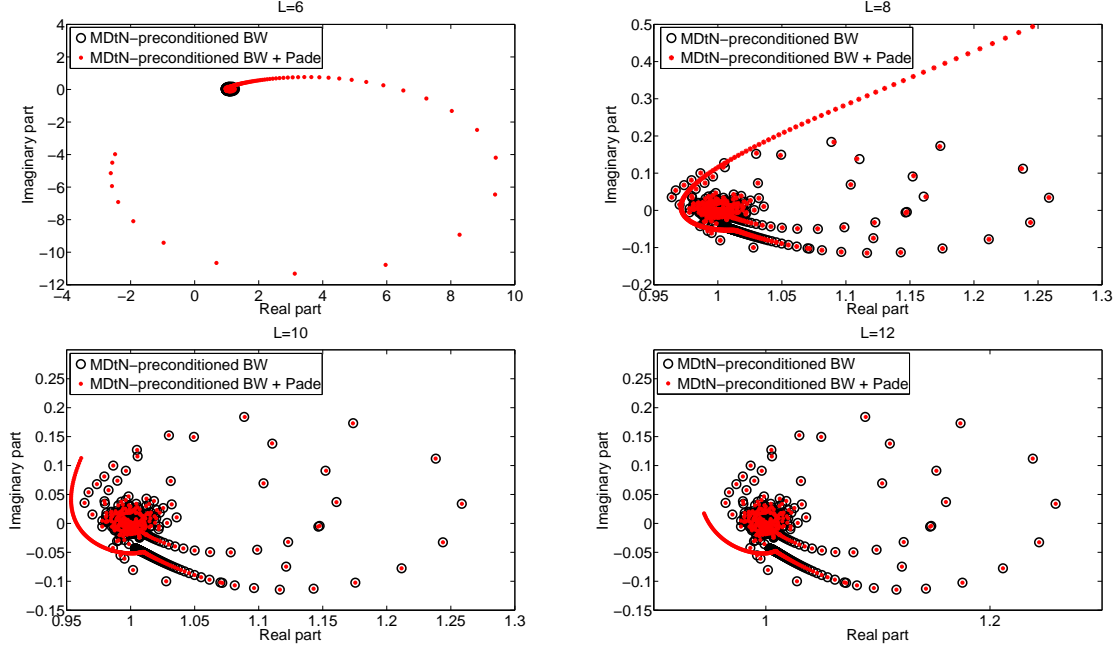


FIGURE 8. Distribution of the eigenvalues of the MDtN-preconditioned BW integral operator versus Padé order,  $\kappa_s = 32\pi$ ,  $m_{\max} = [3\kappa_s]$ .

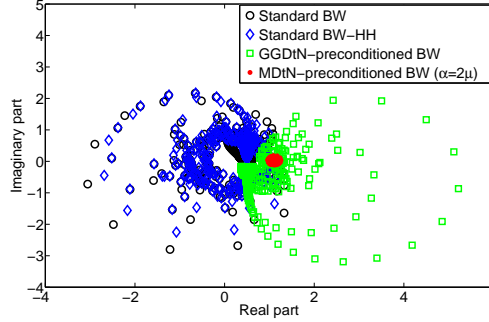


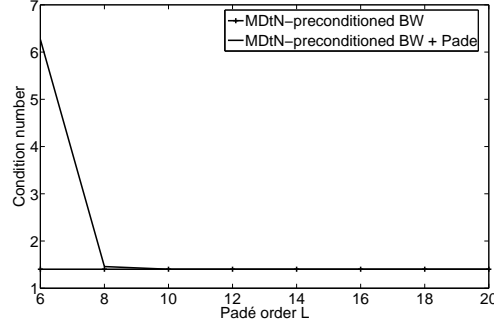
FIGURE 9. Distribution of the eigenvalues of different BW-type integral operators for  $\kappa_s = 32\pi$  and  $m_{\max} = [3\kappa_s]$ .

independently of  $\kappa_s$ . The size of the linear systems varies from 2698 to 17785 in the tests reported in Fig. 11-right. The number of GMRES iterations to solve the standard and MDtN-preconditioned BW integral equation is independent of the truncation parameter  $m_{\max}$ , and is efficiently decreased using the MDtN preconditioning. The iterative solution needs only 7 iterations against 69 for the classical one. These results well fit with the previous spectral observations and validate the robustness of our approach.

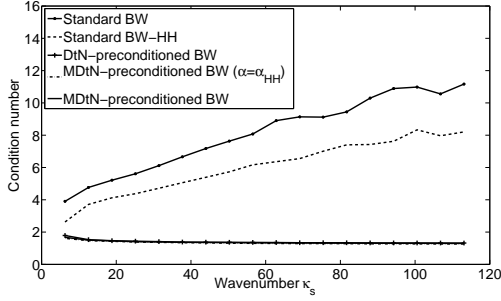
## 5. PRECONDITIONED COMBINED FIELD INTEGRAL EQUATIONS

In this section, we construct in the same way preconditioned CFIEs. Recall that the standard CFIE is expressed by

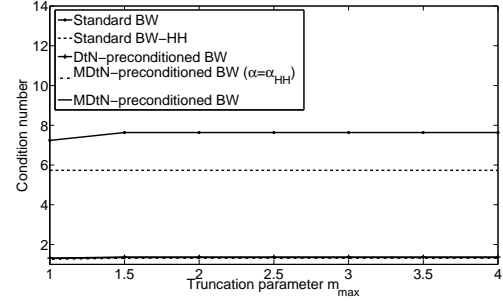
$$\left(\frac{I}{2} + D'_\alpha + i\eta S\right)\varphi = -(\gamma_{1,\alpha}^+ \mathbf{u}^{inc} + i\eta\gamma_0^+ \mathbf{u}^{inc}), \quad \text{on } \Gamma,$$



a) Vs. Padé order,  $\kappa_s = 16\pi$ ,  $m_{\max} = [3\kappa_s]$

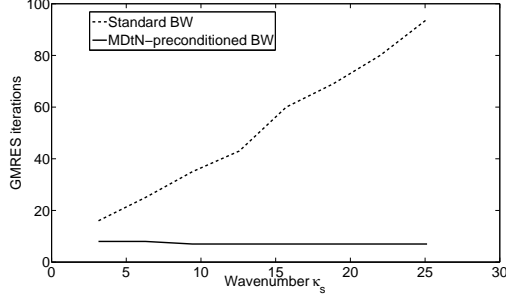


b) Vs.  $\kappa_s$  ( $m_{\max} = [3\kappa_s]$ )

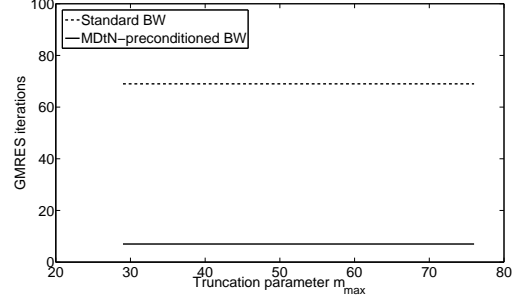


c) Vs.  $m_{\max}$  ( $\kappa_s = 16\pi$ )

FIGURE 10. Unit sphere: Condition number



a) Vs.  $\kappa_s$ ,  $L = 12$ ,  $m_{\max} = [3\kappa_s]$



b) Vs.  $m_{\max}$ ,  $L = 12$ ,  $\kappa_s = 6\pi$

FIGURE 11. Unit sphere: Convergence of GMRES solver

with  $\varphi = -\gamma_1^+(\mathbf{u} + \mathbf{u}^{inc})$  and  $\eta$  a non-zero real constant. The idea is to precondition the operator  $S$  with an approximation of the DtN or of the MDtN operator before combining it with the integral operator  $\frac{I}{2} + D'_\alpha$ . We propose two preconditioned CFIEs:

- A *DtN-preconditioned CFIE* ( $\alpha = 0$ ): Find  $\varphi = -\gamma_1^+(\mathbf{u} + \mathbf{u}^{inc})$  solution to

$$\left(\frac{I}{2} + D' - \Lambda'_\varepsilon S\right)\varphi = -(\gamma_1^+ \mathbf{u}^{inc} - \Lambda'_\varepsilon \gamma_0^+ \mathbf{u}^{inc}), \quad \text{on } \Gamma.$$

- A *MDtN-preconditioned CFIE* ( $\alpha \neq 0$ ): Find  $\varphi = -\gamma_1^+(\mathbf{u} + \mathbf{u}^{inc})$  solution to

$$\left(\frac{I}{2} + D'_\alpha - \Lambda'_{\alpha,\varepsilon} S\right)\varphi = -(\gamma_{1,\alpha}^+ \mathbf{u}^{inc} - \Lambda'_{\alpha,\varepsilon} \gamma_0^+ \mathbf{u}^{inc}), \quad \text{on } \Gamma.$$

These integral operators are the adjoint operators of the DtN- and MDtN-preconditioned BW integral operators (3.15) and (3.24) respectively. Consequently, the two proposed CFIEs are uniquely solvable for any frequency  $\omega > 0$  and damping parameters  $\varepsilon_s > 0$  and  $\varepsilon_p > 0$ . Furthermore, they show the same spectral properties than the proposed indirect preconditioned integral equations, namely an excellent eigenvalue clustering around the point  $(1, 0)$  even for high frequencies, and a condition number independent of both frequency and mesh parameter. These novel CFIEs are therefore well-suited to an iterative Krylov solution, and here the unknown is the physical field.

## 6. SKETCH OF THE NUMERICAL IMPLEMENTATION

In this last section, we suggest ideas to implement the MDtN-preconditioned BW integral equation (3.24). We give elements of discretization to validate the ease of implementation of the proposed analytical preconditioning approach. Let us denote by  $[A]$  the matrix associated with the discretization by finite elements of a given integral operator  $A$ . To solve the MDtN-preconditioned BW integral equation with a GMRES iterative method, one needs to compute at each iteration

$$\mathbf{v} = \left( \frac{1}{2}[\mathbf{I}] + [D_{2\mu}] - [S][\Lambda_{2\mu,\varepsilon}] \right) \mathbf{u},$$

with  $\mathbf{v}, \mathbf{u} \in \mathbb{C}^N$ ,  $N$  the size of the approximation space. The matrix  $[\mathbf{I}]$  represents the mass matrix on the surface mesh.

- First, we apply the MDtN-preconditioner  $\mathbf{w} = [\Lambda_{2\mu,\varepsilon}]\mathbf{u}$ .
- Secondly, we compute the dense matrix-vector products  $\mathbf{v} = \left( \frac{1}{2}[\mathbf{I}] + [D_{2\mu}] \right) \mathbf{u} - [S]\mathbf{w}$  coming from the discretization of the integral operators  $D_{2\mu}$  and  $S$ . The integrals involve singular kernels. These singularities have to be carefully treated. Moreover, the use of FMM [13, 14] is prescribed to efficiently evaluate these products.

We focus on the application of the MDtN-preconditioner: computation of  $\mathbf{w} = [\Lambda_{2\mu,\varepsilon}]\mathbf{u}$ . The regularizing operator  $\Lambda_{2\mu,\varepsilon}$  is given by  $\Lambda_{2\mu,\varepsilon} = P_{1,\varepsilon}(N_{2\mu}) \left( \frac{I}{2} + P_{0,\varepsilon}(D_{2\mu}) \right)^{-1}$ . First, we have to solve

$$(6.1) \quad \left( \frac{[\mathbf{I}]}{2} + [P_{0,\varepsilon}(D_{2\mu})] \right) \mathbf{q} = \mathbf{u},$$

and secondly to realize

$$(6.2) \quad \mathbf{w} = [P_{1,\varepsilon}(N_{2\mu})]\mathbf{q}.$$

We explain the different steps to implement (6.1)-(6.2). Suppose that we know  $\mathbf{u} \in RT$  ( $RT$  is well-known lower-order Raviart-Thomas space [38]).

- Step 1: We determine the Helmholtz decomposition of  $\mathbf{u}$  such that

$$\mathbf{u} \approx \mathbf{curl}_\Gamma \varphi_{\mathbf{u}} + \nabla_\Gamma \psi_{\mathbf{u}} + \mathbf{n} \phi_{\mathbf{u}}.$$

- Step 2: We propose to solve (6.1) with an iterative solver. At each iteration, we have to perform  $\mathbf{y} = \left( \frac{[\mathbf{I}]}{2} + [P_{0,\varepsilon}(D_{2\mu})] \right) \mathbf{x}$ . After determining the three scalar potentials  $(\varphi_{\mathbf{x}}, \psi_{\mathbf{x}}, \phi_{\mathbf{x}})$  of  $\mathbf{x}$ , we obtain easily the potentials of  $\mathbf{y}$  given by

$$\begin{cases} \varphi_{\mathbf{y}} &= \frac{1}{2} \varphi_{\mathbf{x}}, \\ \psi_{\mathbf{y}} &= \frac{1}{2} \left( \psi_{\mathbf{x}} - \frac{1}{\kappa_{p,\varepsilon}} \left( [\mathbf{I}] + \frac{[\Delta_\Gamma]}{\kappa_{p,\varepsilon}^2} \right)^{-1/2} \phi_{\mathbf{x}} \right), \\ \phi_{\mathbf{y}} &= \frac{1}{2} \left( \phi_{\mathbf{x}} + \frac{i}{\kappa_{s,\varepsilon}} \left( [\mathbf{I}] + \frac{[\Delta_\Gamma]}{\kappa_{s,\varepsilon}^2} \right)^{-1/2} [\Delta_\Gamma] \psi_{\mathbf{x}} \right), \end{cases}$$

and we have

$$\mathbf{y} \approx \mathbf{curl}_\Gamma \varphi_{\mathbf{y}} + \nabla_\Gamma \psi_{\mathbf{y}} + \mathbf{n} \phi_{\mathbf{y}}.$$

The matrix  $-\Delta_\Gamma$  is the rigidity matrix on the surface mesh.

- Step 3: We have obtained  $\mathbf{q}$  in the previous step. We determine three scalar potentials  $(\varphi_{\mathbf{q}}, \psi_{\mathbf{q}}, \phi_{\mathbf{q}})$  of  $\mathbf{q}$  such that

$$\mathbf{q} \approx \mathbf{curl}_{\Gamma} \varphi_{\mathbf{q}} + \nabla_{\Gamma} \psi_{\mathbf{q}} + \mathbf{n} \phi_{\mathbf{q}}.$$

- Step 4: We compute (cf. (6.2))

$$\mathbf{w} \approx \mathbf{curl}_{\Gamma} \varphi_{\mathbf{w}} + \nabla_{\Gamma} \psi_{\mathbf{w}} + \mathbf{n} \phi_{\mathbf{w}}.$$

with

$$\begin{cases} \varphi_{\mathbf{w}} &= \frac{i}{2\mu\kappa_{s,\varepsilon}} \left( [\mathbb{I}] + \frac{[\Delta_{\Gamma}]}{\kappa_{s,\varepsilon}^2} \right)^{-1/2} \varphi_{\mathbf{q}}, \\ \psi_{\mathbf{w}} &= \frac{i\rho\omega^2}{2\kappa_{s,\varepsilon}} \left( [\mathbb{I}] + \frac{[\Delta_{\Gamma}]}{\kappa_{s,\varepsilon}^2} \right)^{-1/2} \psi_{\mathbf{q}}, \\ \phi_{\mathbf{w}} &= \frac{i\rho\omega^2}{2\kappa_{p,\varepsilon}} \left( [\mathbb{I}] + \frac{[\Delta_{\Gamma}]}{\kappa_{p,\varepsilon}^2} \right)^{-1/2} \phi_{\mathbf{q}}. \end{cases}$$

To efficiently localize the different inverse square-root operators  $(1+z)^{-1/2}$ , we use complex Padé approximants of order  $(2L+1)$  applying a rotating of the usual branch-cut  $\{z \in \mathbb{R}, z < -1\}$  with an angle  $\theta$ . We have

$$\left( [\mathbb{I}] + \frac{[\Delta_{\Gamma}]}{\kappa^2} \right)^{-1/2} \approx r_0 [\mathbb{I}] + \sum_{j=1}^L r_j \left( \frac{[\Delta_{\Gamma}]}{\kappa^2} - q_j [\mathbb{I}] \right)^{-1},$$

where  $r_j, j = 0, \dots, L$ , and  $q_j, j = 1, \dots, L$ , are complex coefficients depending on the angle  $\theta$  [8, 34, 35, 7]. To conclude, the implementation of the MDtN-preconditioner requires only the solution of sparse linear systems involving mass and rigidity matrices, and the numerical determination of the Helmholtz decomposition of a vector defined in  $RT$ .

## 7. CONCLUSION AND PERSPECTIVES

In this paper, we have built well-conditioned integral equations for the iterative solution of Dirichlet elastic scattering problems. The preconditioning strategy is based on a rewriting of the Somigliana integral representation of the scattered field. A regularizing operator is incorporated and forces the integral equations arising from this representation to have ideal spectral properties for an iterative solution. Two regularizing operators are proposed: an approximation of the exact DtN operator and an approximation of a Modified DtN operator. The second preconditioner is more suited to a numerical implementation. It is expressed using the principal parts of the elementary boundary integral operators, namely surface differential operators and square-root operators.

A numerical investigation of the eigenvalues of the standard and preconditioned integral operators for the spherical case illustrates the efficiency of the approach. The eigenvalues of the preconditioned formulations are well clustered and their condition number is close to 1 independently of both a frequency increase and a mesh refinement. This leads to a fast convergence of the GMRES iterative solver. These first results are very encouraging. Furthermore, the proposed preconditioner shows highly-desirable advantages: sparse structure, ease of implementation and a low additional computational cost using Padé approximants to localize the square-root operators.

The numerical implementation and validation of this analytical preconditioning approach for more general obstacles will be challenging future works. A combination with the FMM seems promising. A previous work in acoustic scattering [20] has shown significant improvements for the computational time and cost of the solution. It would be very interesting to test first the numerical accuracy of the MDtN approximation in the OSRC context, before applying it as a preconditioner.

### Acknowledgments.

The authors would like to thank the anonymous referees for useful comments and suggestions. This work was supported in part by the French ANR grant MicroWave NT09 460489 (ÔProgramme BlancÔ call).

## APPENDIX Appendix

In this appendix, we give the spectral decomposition of the different elastic boundary integral operators in terms of the vector spherical harmonics.

Notations. Let us introduce the spherical harmonics  $Y_{m,\ell}$  as the functions of order  $m$  for  $\ell = -m, \dots, m$ , with  $m, \ell \in \mathbb{N}$  given by [17]

$$Y_{m,\ell}(\hat{\mathbf{x}}) = (-1)^{\frac{|\ell|+\ell}{2}} \sqrt{\frac{2m+1}{4\pi} \frac{(m-|\ell|)!}{(m+|\ell|)!}} P_m^{|\ell|}(\cos\theta) e^{i\ell\phi}, \quad \hat{\mathbf{x}}(\theta, \phi) \in \mathbb{S}^2,$$

where  $P_m^\ell$  denote the  $\ell$ -th associated Legendre polynomials of order  $m$ . The tangential vector spherical harmonics defined by

$$\mathbf{Y}_{m,\ell}^{(1)} = \frac{1}{\sqrt{m(m+1)}} \nabla_{\mathbb{S}^2} Y_{m,\ell}, \quad \mathbf{Y}_{m,\ell}^{(2)} = \frac{1}{\sqrt{m(m+1)}} \mathbf{curl}_{\mathbb{S}^2} Y_{m,\ell} = \mathbf{Y}_{m,\ell}^{(1)} \times \hat{\mathbf{x}},$$

for  $\ell = -m, \dots, m$  and  $m = 1, 2, \dots$  together with the normal vector spherical harmonics  $\mathbf{Y}_{m,\ell}^{(3)} = \hat{\mathbf{x}} Y_{m,\ell}$ , for  $\ell = -m, \dots, m$  and  $m = 0, 1, 2, \dots$  form a complete orthonormal system in  $\mathbf{L}^2(\mathbb{S}^2)$  undowed with the hermitian product

$$(\varphi_1 | \varphi_2)_{\mathbb{S}^2} = \int_{\mathbb{S}^2} \varphi_1(\hat{\mathbf{x}}) \cdot \overline{\varphi_2(\hat{\mathbf{x}})} ds(\hat{\mathbf{x}}).$$

Let us denote by  $j_m$  the spherical Bessel function of order  $m \in \mathbb{N}$  and by  $h_m^{(1)}$  the spherical Hankel function of the first kind and order  $m \in \mathbb{N}$ . We set  $z_m^{(1)} = j_m$  and  $z_m^{(3)} = h_m^{(1)}$  and

$$u_{m,\ell}^{(k)}(\kappa, \mathbf{x}) = z_m^{(k)}(\kappa|\mathbf{x}|) Y_{m,\ell}(\hat{\mathbf{x}}), \quad M_{m,\ell}^{(k)}(\kappa, \mathbf{x}) = \mathbf{curl}(\mathbf{x} u_{m,\ell}^{(k)}(\kappa, \mathbf{x})), \quad N_{m,\ell}^{(k)}(\kappa, \mathbf{x}) = \frac{1}{i\kappa} \mathbf{curl} M_{m,\ell}^{(k)}(\kappa, \mathbf{x}).$$

Then, the fundamental solution of the Navier equation admits the following series expansion for  $|\mathbf{x}| > |\mathbf{y}|$ :

$$\begin{aligned} \Phi(\mathbf{x}, \mathbf{y}) &= \frac{i\kappa_s}{\mu} \sum_{m=1}^{\infty} \frac{1}{m(m+1)} \sum_{\ell=-m}^m M_{m,\ell}^{(3)}(\kappa_s, \mathbf{x}) \otimes \overline{M_{m,\ell}^{(1)}(\kappa_s, \mathbf{y})} \\ &+ \frac{i\kappa_s}{\mu} \sum_{m=1}^{\infty} \frac{1}{m(m+1)} \sum_{\ell=-m}^m N_{m,\ell}^{(3)}(\kappa_s, \mathbf{x}) \otimes \overline{N_{m,\ell}^{(1)}(\kappa_s, \mathbf{y})} \\ &+ \frac{i}{\kappa_p(\lambda+2\mu)} \sum_{m=0}^{\infty} \sum_{\ell=-m}^m \nabla u_{m,\ell}^{(3)}(\kappa_p, \mathbf{x}) \otimes \overline{\nabla u_{m,\ell}^{(1)}(\kappa_p, \mathbf{y})} \end{aligned}$$

where  $\otimes$  is the tensor product. We denote by  $\xi_m^{(1)}(t) = th_m^{(1)}(t)$  et  $\psi_m(t) = tj_m(t)$  the Ricatti-Hankel and Ricatti-Bessel functions of order  $m$  respectively.

Spectral decomposition of the elementary boundary integral operators. In the case of the scattering by an elastic sphere of radius  $R$ , we have  $S\mathcal{Y}_{0,0}^{(3)} = S_0^{(3,3)}\mathcal{Y}_{0,0}^{(3)}$  and for  $m \geq 1$  and  $\ell = -m, \dots, m$ ,

$$S \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} S_m^{(1,1)} & 0 & S_m^{(1,3)} \\ 0 & S_m^{(2,2)} & 0 \\ S_m^{(3,1)} & 0 & S_m^{(3,3)} \end{pmatrix} \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix}$$

with, for  $m \geq 1$

$$\begin{aligned} S_m^{(1,1)} &= \frac{i}{\mu\kappa_s} \psi'_m(\kappa_s R) \xi_m^{(1)'}(\kappa_s R) + \frac{i}{\kappa_p(\lambda+2\mu)} m(m+1) j_m(\kappa_p R) h_m^{(1)}(\kappa_p R), \\ S_m^{(3,1)} &= \frac{i}{\mu\kappa_s} \frac{\sqrt{m(m+1)}}{2} \left[ j_m(\kappa_s R) \xi_m^{(1)'}(\kappa_s R) + h_m^{(1)}(\kappa_s R) \psi'_m(\kappa_s R) \right] \\ &+ \frac{iR}{(\lambda+2\mu)} \frac{\sqrt{m(m+1)}}{2} \left[ h_m^{(1)'}(\kappa_p R) j_m(\kappa_p R) + j'_m(\kappa_p R) h_m^{(1)}(\kappa_p R) \right], \\ S_m^{(2,2)} &= \frac{i}{\mu\kappa_s} \psi_m(\kappa_s R) \xi_m^{(1)}(\kappa_s R), \\ S_m^{(1,3)} &= S_m^{(3,1)}, \end{aligned}$$

and for  $m \geq 0$

$$S_m^{(3,3)} = \frac{i}{\mu\kappa_s} m(m+1) j_m(\kappa_s R) h_m^{(1)}(\kappa_s R) + \frac{i\kappa_p R^2}{(\lambda+2\mu)} j'_m(\kappa_p R) h_m^{(1)'}(\kappa_p R).$$

We also have  $D' = D^T$ ,  $D\mathcal{Y}_{0,0}^{(3)} = D_0^{(3,3)}\mathcal{Y}_{0,0}^{(3)}$  and for  $m \geq 1$  and  $\ell = -m, \dots, m$ ,

$$D \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} D_m^{(1,1)} & 0 & D_m^{(1,3)} \\ 0 & D_m^{(2,2)} & 0 \\ D_m^{(3,1)} & 0 & D_m^{(3,3)} \end{pmatrix} \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix}$$

with, for  $m \geq 1$

$$\begin{aligned} D_m^{(1,1)} &= -\frac{i}{\kappa_s R} \left[ \left( (\kappa_s^2 R^2 - m(m+1) + 1) h_m^{(1)}(\kappa_s R) + \kappa_s R h_m^{(1)'}(\kappa_s R) \right) \psi'_m(\kappa_s R) \right. \\ &\quad + \left( (\kappa_s^2 R^2 - m(m+1) + 1) j_m(\kappa_s R) + \kappa_s R j'_m(\kappa_s R) \right) \xi_m^{(1)'}(\kappa_s R) \Big] \\ &\quad + \frac{i\kappa_s R}{2} \left( h_m^{(1)}(\kappa_s R) \psi'_m(\kappa_s R) + j_m(\kappa_s R) \xi_m^{(1)'}(\kappa_s R) \right) \\ &\quad + \frac{i\mu m(m+1)}{\kappa_p R(\lambda + 2\mu)} \left[ h_m^{(1)}(\kappa_p R) \psi'_m(\kappa_p R) + j_m(\kappa_p R) \xi_m^{(1)'}(\kappa_p R) - 4j_m(\kappa_p R) h_m^{(1)}(\kappa_p R) \right], \\ D_m^{(1,3)} &= \frac{2i\sqrt{m(m+1)}}{\kappa_s R} \left[ \psi'_m(\kappa_s R) \xi_m^{(1)'}(\kappa_s R) - j_m(\kappa_s R) \xi_m^{(1)'}(\kappa_s R) - h_m^{(1)}(\kappa_s R) \psi'_m(\kappa_s R) \right] \\ &\quad + \frac{\mu\sqrt{m(m+1)}}{i\kappa_p R(\lambda + 2\mu)} \left[ j_m(\kappa_p R) \left( (\kappa_p^2 R^2 - m(m+1)) h_m^{(1)}(\kappa_p R) + 2\kappa_p R h_m^{(1)'}(\kappa_p R) \right) \right. \\ &\quad + h_m^{(1)}(\kappa_p R) \left( (\kappa_p^2 R^2 - m(m+1)) j_m(\kappa_p R) + 2\kappa_p R j'_m(\kappa_p R) \right) \Big] \\ &\quad - \frac{i\lambda\kappa_p R\sqrt{m(m+1)}}{(\lambda + 2\mu)} j_m(\kappa_p R) h_m^{(1)}(\kappa_p R), \\ D_m^{(2,2)} &= i(\kappa_s R)^2 \left( j'_m(\kappa_s R) h_m^{(1)}(\kappa_s R) + h_m^{(1)'}(\kappa_s R) j_m(\kappa_s R) \right) \\ &\quad - \frac{i\kappa_s R}{2} \left( j_m(\kappa_s R) \xi_m^{(1)'}(\kappa_s R) + h_m^{(1)}(\kappa_s R) \psi'_m(\kappa_s R) \right), \\ D_m^{(3,1)} &= \frac{\sqrt{m(m+1)}}{i\kappa_s R} \left[ j_m(\kappa_s R) \left( (\kappa_s^2 R^2 - m(m+1) + 1) h_m^{(1)}(\kappa_s R) + \kappa_s R h_m^{(1)'}(\kappa_s R) \right) \right. \\ &\quad + h_m^{(1)}(\kappa_s R) \left( (\kappa_s^2 R^2 - m(m+1) + 1) j_m(\kappa_s R) + \kappa_s R j'_m(\kappa_s R) \right) \Big] \\ &\quad + i\kappa_s R \sqrt{m(m+1)} j_m(\kappa_s R) h_m^{(1)}(\kappa_s R) \\ &\quad + \frac{i\mu\sqrt{m(m+1)}}{(\lambda + 2\mu)} \left[ 2\kappa_p R j'_m(\kappa_p R) h_m^{(1)'}(\kappa_p R) - j_m(\kappa_p R) h_m^{(1)'}(\kappa_p R) - j'_m(\kappa_p R) h_m^{(1)}(\kappa_p R) \right], \end{aligned}$$

and for  $m \geq 0$

$$\begin{aligned} D_m^{(3,3)} &= \frac{im(m+1)}{\kappa_s} \left[ h_m^{(1)}(\kappa_s R) \left( \kappa_s j'_m(\kappa_s R) - \frac{j_m(\kappa_s R)}{R} \right) + j_m(\kappa_s R) \left( \kappa_s h_m^{(1)'}(\kappa_s R) - \frac{h_m^{(1)}(\kappa_s R)}{R} \right) \right] \\ &\quad - \frac{i\mu}{(\lambda + 2\mu)} \left[ j'_m(\kappa_p R) \left( (\kappa_p^2 R^2 - m(m+1)) h_m^{(1)}(\kappa_p R) + 2\kappa_p R h_m^{(1)'}(\kappa_p R) \right) \right. \\ &\quad + h_m^{(1)'}(\kappa_p R) \left( (\kappa_p^2 R^2 - m(m+1)) j_m(\kappa_p R) + 2\kappa_p R j'_m(\kappa_p R) \right) \Big] \\ &\quad - \frac{i(\kappa_p R)^2 \lambda}{2(\lambda + 2\mu)} \left( j_m(\kappa_p R) h_m^{(1)'}(\kappa_p R) + j'_m(\kappa_p R) h_m^{(1)}(\kappa_p R) \right). \end{aligned}$$

We have  $N\mathcal{Y}_{0,0}^{(3)} = N_0^{(3,3)}\mathcal{Y}_{0,0}^{(3)}$  and for  $m \geq 1$  and  $\ell = -m, \dots, m$

$$N \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} N_m^{(1,1)} & 0 & N_m^{(1,3)} \\ 0 & N_m^{(2,2)} & 0 \\ N_m^{(3,1)} & 0 & N_m^{(3,3)} \end{pmatrix} \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix}$$

where for  $m \geq 1$

$$\begin{aligned}
N_m^{(1,1)} &= \frac{i\mu}{\kappa_s R^2} \left( (\kappa_s^2 R^2 - 2m(m+1) + 2) h_m^{(1)}(\kappa_s R) + 2\kappa_s R h_m^{(1)'}(\kappa_s R) \right) \\
&\quad \times \left( (\kappa_s^2 R^2 - 2m(m+1) + 2) j_m(\kappa_s R) + 2\kappa_s R j_m'(\kappa_s R) \right) \\
&\quad + \frac{4i\mu^2 m(m+1)}{\kappa_p(\lambda + 2\mu)} \left( \kappa_p h_m^{(1)'}(\kappa_p R) - \frac{h_m^{(1)}(\kappa_p R)}{R} \right) \left( \kappa_p j_m'(\kappa_p R) - \frac{j_m(\kappa_p R)}{R} \right), \\
N_m^{(3,1)} &= \frac{\mu\sqrt{m(m+1)}}{i\kappa_s R} \left[ \left( (\kappa_s^2 R^2 - 2m(m+1)) h_m^{(1)}(\kappa_s R) + 2\xi_m^{(1)}(\kappa_s R) \right) \left( \kappa_s j_m'(\kappa_s R) - \frac{j_m(\kappa_s R)}{R} \right) \right. \\
&\quad \left. + \left( (\kappa_s^2 R^2 - 2m(m+1)) j_m(\kappa_s R) + 2\psi_m(\kappa_s R) \right) \left( \kappa_s h_m^{(1)'}(\kappa_s R) - \frac{h_m^{(1)}(\kappa_s R)}{R} \right) \right] \\
&\quad - \frac{i\mu R\sqrt{m(m+1)}}{\kappa_p(\lambda + 2\mu)} \left\{ \left[ \frac{2\mu}{R^2} \left( (\kappa_p^2 R^2 - m(m+1)) h_m^{(1)}(\kappa_p R) + 2\kappa_p R h_m^{(1)'}(\kappa_p R) \right) + \lambda\kappa_p^2 h_m^{(1)}(\kappa_p R) \right] \right. \\
&\quad \times \left( \kappa_p j_m'(\kappa_p R) - \frac{j_m(\kappa_p R)}{R} \right) \\
&\quad \left. + \left[ \frac{2\mu}{R^2} \left( (\kappa_p^2 R^2 - m(m+1)) j_m(\kappa_p R) + 2\kappa_p R j_m'(\kappa_p R) \right) + \lambda\kappa_p^2 j_m(\kappa_p R) \right] \right. \\
&\quad \left. \times \left( \kappa_p h_m^{(1)'}(\kappa_p R) - \frac{h_m^{(1)}(\kappa_p R)}{R} \right) \right\}, \\
N_m^{(2,2)} &= i\mu\kappa_s R^2 \left( \kappa_s j_m'(\kappa_s R) - \frac{j_m(\kappa_s R)}{R} \right) \left( \kappa_s h_m^{(1)'}(\kappa_s R) - \frac{h_m^{(1)}(\kappa_s R)}{R} \right), \\
N_m^{(1,3)} &= N_m^{(3,1)},
\end{aligned}$$

and for  $m \geq 0$

$$\begin{aligned}
N_m^{(3,3)} &= 4i\mu \frac{m(m+1)}{\kappa_s} \left( \kappa_s h_m^{(1)'}(\kappa_s R) - \frac{h_m^{(1)}(\kappa_s R)}{R} \right) \left( \kappa_s j_m'(\kappa_s R) - \frac{j_m(\kappa_s R)}{R} \right) \\
&\quad + \frac{iR^2}{\kappa_p(\lambda + 2\mu)} \left[ \frac{2\mu}{R^2} \left( (\kappa_p^2 R^2 - m(m+1)) h_m^{(1)}(\kappa_p R) + 2\kappa_p R h_m^{(1)'}(\kappa_p R) \right) + \lambda\kappa_p^2 h_m^{(1)}(\kappa_p R) \right] \\
&\quad \times \left[ \frac{2\mu}{R^2} \left( (\kappa_p^2 R^2 - m(m+1)) j_m(\kappa_p R) + 2\kappa_p R j_m'(\kappa_p R) \right) + \lambda\kappa_p^2 j_m(\kappa_p R) \right].
\end{aligned}$$

Associated principal parts. We give the spectral decomposition of the principal parts  $P_{-1}(S)$ ,  $P_0(D)$  and  $P_1(N)$  of the integral operators  $S$ ,  $D$  and  $N$  respectively (see Section 2.1). By recalling that the eigenvalues of the surface operator  $\Delta_\Gamma$  are given by  $-m(m+1)/R^2$ , we have the following results

$$P_{-1}(S) \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} s_m^{(1,1)} & 0 & 0 \\ 0 & s_m^{(2,2)} & 0 \\ 0 & 0 & s_m^{(3,3)} \end{pmatrix} \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix},$$

with

$$\begin{aligned}
s_m^{(1,1)} &= \frac{i}{2\rho\omega^2} \left[ \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{m(m+1)}{R^2} \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}} \right], \\
s_m^{(2,2)} &= \frac{i}{2\rho\omega^2} \kappa_s^2 \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}}, \\
s_m^{(3,3)} &= \frac{i}{2\rho\omega^2} \left[ \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{m(m+1)}{R^2} \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}} \right],
\end{aligned}$$

$$P_0(D) \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} 0 & 0 & d_m^{(1,3)} \\ 0 & 0 & 0 \\ d_m^{(3,1)} & 0 & 0 \end{pmatrix} \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix},$$



with

$$\begin{aligned}
d_m^{(1,3)} &= \frac{i}{\kappa_s^2} \left( \frac{m(m+1)}{R^2} \right)^{1/2} \left[ \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{m(m+1)}{R^2} \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}} \right] \\
&\quad - \frac{i}{2} \left( \frac{m(m+1)}{R^2} \right)^{1/2} \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}}, \\
d_m^{(3,1)} &= \frac{i}{\kappa_s^2} \left( \frac{m(m+1)}{R^2} \right)^{1/2} \left[ \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{m(m+1)}{R^2} \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}} \right] \\
&\quad - \frac{i}{2} \left( \frac{m(m+1)}{R^2} \right)^{1/2} \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}},
\end{aligned}$$

and, finally,

$$P_1(N) \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix} = \begin{pmatrix} n_m^{(1,1)} & 0 & 0 \\ 0 & n_m^{(2,2)} & 0 \\ 0 & 0 & n_m^{(3,3)} \end{pmatrix} \begin{pmatrix} \mathcal{Y}_{m,\ell}^{(1)} \\ \mathcal{Y}_{m,\ell}^{(2)} \\ \mathcal{Y}_{m,\ell}^{(3)} \end{pmatrix},$$

with

$$\begin{aligned}
n_m^{(1,1)} &= \frac{i}{2\rho\omega^2} \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{2i\mu}{\kappa_s^2} \frac{m(m+1)}{R^2} \left[ \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{m(m+1)}{R^2} \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}} \right] \\
&\quad - 2i\mu \left( \frac{m(m+1)}{R^2} \right)^{1/2} \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}}, \\
n_m^{(2,2)} &= \frac{i}{2} \mu \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}}, \\
n_m^{(3,3)} &= \frac{i}{2\rho\omega^2} \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{2i\mu}{\kappa_s^2} \frac{m(m+1)}{R^2} \left[ \left( \kappa_s^2 - \frac{m(m+1)}{R^2} \right)^{\frac{1}{2}} + \frac{m(m+1)}{R^2} \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}} \right] \\
&\quad - 2i\mu \left( \frac{m(m+1)}{R^2} \right)^{1/2} \left( \kappa_p^2 - \frac{m(m+1)}{R^2} \right)^{-\frac{1}{2}}.
\end{aligned}$$

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