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The T-coercivity approach for mixed problems

T-coercivité et problèmes mixtes

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This article is dedicated to Professor Franco Brezzi by the second author, with admiration.

Abstract. Classically, the well-posedness of variational formulations of mixed linear problems is achieved through the inf-sup condition on the constraint. In this note, we propose an alternative framework to study such problems by using the T-coercivity approach to derive a global inf-sup condition. Generally speaking, this is a constructive approach that, in addition, drives the design of suitable approximations. As a matter of fact, the derivation of the uniform discrete inf-sup condition for the approximate problems follows easily from the study of the original problem. To support our view, we solve a series of classical mixed problems with the T-coercivity approach. Among others, the celebrated Fortin Lemma appears naturally in the numerical analysis of the approximate problems.

Résumé. Classiquement, le caractère bien posé des formulations variationnelles de problèmes linéaires mixtes est obtenu à l'aide de la condition inf-sup sur la contrainte. Dans cette note, nous proposons un cadre alternatif pour étudier de tels problèmes en utilisant la notion de T-coercivité pour obtenir une condition inf-sup globale. Il s'agit d'une approche constructive qui permet en outre de concevoir simplement des approximations numériques adaptées car la dérivation de la condition inf-sup discrète uniforme découle en général directement de l'étude du problème continu. Pour appuyer notre propos, nous résolvons une série de problèmes mixtes classiques grâce à la notion de T-coercivité. Entre autres, le lemme de Fortin apparaît naturellement dans l'analyse numérique des problèmes discrets.

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1. Introduction

Traditionally, the well-posedness of variational formulations of mixed linear problems is achieved through the inf-sup condition, also called stability condition [2, 12, 42]. As a matter of fact, proving this condition allows to derive existence and uniqueness of the solution, and continuous dependence with respect to the data. On the other hand, the way this condition is established depends on the problem to be solved. The analysis of such problems can be performed either following a *monolithic* approach, namely studying the *all-in-one* bilinear form incorporating the constraint, or by studying the constrained part of the problem separately.

In this note, we focus on the monolithic approach and investigate the mixed problem's well-posedness based on the T-coercivity framework. The principle of this framework is to find an *explicit realization* of the inf-sup condition for the all-in-one bilinear form. Of equal importance, in the T-coercivity framework, is the *design of suitable approximations* of the original problem. Indeed, with the help of the explicit realization of the condition for the original problem, one can get useful insight on how to derive the so-called uniform discrete inf-sup condition for the approximate, or discrete, problems set in finite-dimensional vector spaces. Thus, convergence of the approximate solutions to the exact one follows under well-known principles in numerical analysis, such as Céa's Lemma (or a variant), and a basic approximability property of elements of the original space of solutions. To summarize, although the T-coercivity approach may not bring new result to the theory of variational formulations, it holds two key features: it proposes a compact way to study them theoretically; it provides useful insight on how to approximate them.

So far, the T-coercivity approach has been mainly applied to two categories of linear problems. First, for problems involving an invertible operator and a compact perturbation, see eg. [13–16, 24, 37, 38, 45, 46]. Then, for problems with sign-changing coefficients, cf. [6–11, 17–23, 25, 27, 35, 36, 44]. For the second category, we observe that well-posedness and (efficient) approximation of the variational formulations has actually been achieved with the help of the T-coercivity approach. Up to the authors' knowledge, this approach was only applied to mixed problems in [28, 41] and [39]: the last reference focuses on perturbed saddle-point problems, whereas the other two deal with the specific case of neutron diffusion.

In this note, we apply the T-coercivity approach to general mixed problems, including unperturbed and perturbed saddle-point problems. In particular, we will explain the connections with the classical theory, for which we use [5] as the reference textbook. Among those connections, we note that the celebrated Fortin Lemma will appear naturally in the (numerical) analysis of the discrete problems.

Let us introduce some notation. Given a Hilbert space V , we denote by $(\cdot, \cdot)_V$ and $\|\cdot\|_V$ the inner product and the norm on V , and by V' its dual space. In a product space $V \times W$ of two Hilbert spaces, we use the norm

$$\|(v, w)\|_{V \times W} = (\|v\|_V^2 + \|w\|_W^2)^{1/2},$$

and similarly for the inner product. Let $\mathcal{L}(V, W)$ denote the set of bounded operators from V to W . In $\mathcal{L}(V, W)$, we use the norm

$$\|A\| = \sup_{v \in V \setminus \{0\}} \frac{\|Av\|_W}{\|v\|_V}.$$

If $V = W$ we use the notation $\mathcal{L}(V)$.

Vector-valued function spaces are written in boldface character. A connected, bounded, open subset of \mathbb{R}^d with a Lipschitz boundary is called a *domain*.

Let Ω be a domain with boundary $\partial\Omega$. We denote by \mathbf{n} the unit outward normal vector field to $\partial\Omega$. Let $L^2(\Omega)$ and $\mathbf{L}^2(\Omega)$ be the set of square-integrable real-valued and \mathbb{R}^d -valued functions on Ω . The natural norm in $L^2(\Omega)$ or $\mathbf{L}^2(\Omega)$ is denoted by $\|\cdot\|$, and we let

$$L_0^2(\Omega) = \left\{ v \in L^2(\Omega), \int_{\Omega} v \, dx = 0 \right\}.$$

In what follows, unless otherwise stated, the standard Sobolev space $H_0^1(\Omega)$ is endowed with the norm $v \mapsto \|\nabla v\|$, that defines a norm that is equivalent to $\|\cdot\|_{H^1(\Omega)}$ thanks to Poincaré’s inequality. The dual space of $H_0^1(\Omega)$ is denoted by $H^{-1}(\Omega)$. Similarly, $\mathbf{H}_0^1(\Omega)$ is endowed with the norm $\mathbf{v} \mapsto (\sum_{i=1,d} \|\nabla v_i\|^2)^{1/2}$, that defines a norm that is equivalent to $\|\cdot\|_{\mathbf{H}^1(\Omega)}$, and its dual space is denoted by $\mathbf{H}^{-1}(\Omega)$. We introduce the usual Sobolev spaces for vector-valued fields [1]

$$\begin{aligned} \mathbf{H}(\text{div}; \Omega) &= \{ \mathbf{v} \in \mathbf{L}^2(\Omega), \text{div } \mathbf{v} \in L^2(\Omega) \}, \\ \mathbf{H}_0(\text{div}; \Omega) &= \{ \mathbf{v} \in \mathbf{H}(\text{div}; \Omega), \mathbf{v} \cdot \mathbf{n} = 0 \text{ on } \partial\Omega \}, \\ \mathbf{H}(\text{div}0; \Omega) &= \{ \mathbf{v} \in \mathbf{H}(\text{div}; \Omega), \text{div } \mathbf{v} = 0 \}, \\ \mathbf{H}(\text{curl}; \Omega) &= \{ \mathbf{v} \in \mathbf{L}^2(\Omega), \text{curl } \mathbf{v} \in \mathbf{L}^2(\Omega) \}, & \text{for } d = 3, \\ \mathbf{H}_0(\text{curl}; \Omega) &= \{ \mathbf{v} \in \mathbf{H}(\text{curl}; \Omega), \mathbf{v} \times \mathbf{n} = 0 \text{ on } \partial\Omega \}, & \text{for } d = 3. \end{aligned}$$

Unless otherwise specified, $\mathbf{H}(\text{div}; \Omega)$ is endowed with the norm $\mathbf{v} \mapsto (\|\mathbf{v}\|^2 + \|\text{div } \mathbf{v}\|^2)^{1/2}$ and $\mathbf{H}(\text{curl}; \Omega)$ with the norm $\mathbf{v} \mapsto (\|\mathbf{v}\|^2 + \|\text{curl } \mathbf{v}\|^2)^{1/2}$.

The outline is as follows. In Section 2, we introduce the T-coercivity approach, and explain how it can be applied to solve the Stokes problem theoretically. Then, in Section 3, we develop the abstract framework underlying the approach for mixed problems, including saddle-point, augmented and perturbed ones. In Sections 4, 5 and 6, we propose some applications, respectively to electromagnetism, nearly-incompressible elasticity, and diffusion. Then, in Section 7, we propose the *natural* extension of the T-coercivity approach for the conforming approximation of mixed problems. As before, we begin by the Stokes problem, then we consider the numerical analysis for mixed problems in general, before describing how the approach can be applied to electromagnetism, nearly-incompressible elasticity, and diffusion. We conclude by a list of further extensions and recent applications of the T-coercivity approach.

2. T-coercivity for the Stokes problem

The starting point of our study is to propose a T-coercivity approach to solve Stokes problem. Let $\Omega \subset \mathbb{R}^d$ be a domain. We consider the Stokes problem with homogeneous Dirichlet boundary conditions: given a prescribed body force $\mathbf{f} \in \mathbf{H}^{-1}(\Omega)$, find the velocity $\mathbf{u} \in \mathbf{H}^1(\Omega)$ and the pressure $p \in L_0^2(\Omega)$ such that

$$\begin{aligned} -\nu \Delta \mathbf{u} + \nabla p &= \mathbf{f}, & \text{in } \Omega, \\ \text{div } \mathbf{u} &= 0, & \text{in } \Omega, \\ \mathbf{u} &= 0, & \text{on } \partial\Omega, \end{aligned} \tag{1}$$

where $\nu > 0$ denotes the fluid’s viscosity.

The standard method to solve Problem (1) – see [33] – consists in a *one-plus-one* approach. The problem is split into a coercive part

$$a(\mathbf{u}, \mathbf{v}) = \nu \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v} \, dx$$

and divergence constraint terms of the form

$$b(\mathbf{v}, q) = - \int_{\Omega} q \, \text{div } \mathbf{v} \, dx,$$

so that the weak formulation of Problem (1) reads: find $(\mathbf{u}, p) \in \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)$ such that

$$\begin{aligned} a(\mathbf{u}, \mathbf{v}) + b(\mathbf{v}, p) &= \langle \mathbf{f}, \mathbf{v} \rangle, \quad \forall \mathbf{v} \in \mathbf{H}_0^1(\Omega), \\ b(\mathbf{u}, q) &= 0, \quad \forall q \in L_0^2(\Omega), \end{aligned} \tag{2}$$

where $\langle \cdot, \cdot \rangle$ denotes the duality product in $\mathbf{H}^{-1}(\Omega) \times \mathbf{H}_0^1(\Omega)$. The well-posedness of Problem (2) then follows from Ladyzhenskaya–Babuška–Brezzi’s theory [2, 12, 42] since the bilinear form a is coercive on $\mathbf{H}_0^1(\Omega)$ and the bilinear form b satisfies the *inf-sup condition*

$$\inf_{q \in L_0^2(\Omega) \setminus \{0\}} \sup_{\mathbf{v} \in \mathbf{H}_0^1(\Omega) \setminus \{0\}} \frac{b(\mathbf{v}, q)}{\|\nabla \mathbf{v}\| \|q\|} \geq \underline{\beta} \tag{3}$$

for some constant $\underline{\beta} > 0$.

Here, we are going to give an alternative proof that Problem (1) is well-posed by analysing the *all-in-one* bilinear form defined on $\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)$

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}, q)) = \nu \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v} \, dx - \int_{\Omega} p \operatorname{div} \mathbf{v} \, dx - \int_{\Omega} q \operatorname{div} \mathbf{u} \, dx$$

instead of splitting it into two bilinear forms a and b as in (2). This bilinear form is not coercive since

$$\mathcal{A}((0, p), (0, p)) = 0, \quad \forall p \in L_0^2(\Omega).$$

For this reason, we use the notion of T-coercivity [23, 24], which can be seen as a reformulation of Banach–Nečas–Babuška’s theory [30, Theorem 25.9]. The definition and the main property of T-coercivity are recalled below.

Definition 1 ([23, Definition 3]). *Let W be a Hilbert space and let $\mathcal{A}(\cdot, \cdot)$ be a continuous bilinear form over $W \times W$. We say that \mathcal{A} is T-coercive if there exists a bijective operator $T \in \mathcal{L}(W)$ and $\underline{\alpha} > 0$ such that*

$$|\mathcal{A}(v, Tv)| \geq \underline{\alpha} \|v\|_W^2, \quad \forall v \in W.$$

When the bilinear form $\mathcal{A}(\cdot, \cdot)$ is in addition symmetric, the requirement that the operator T is bijective can be dropped.

Proposition 2 ([23, Theorem 1]). *Let W be a Hilbert space. Let $\ell(\cdot)$ be a continuous linear form over W and $\mathcal{A}(\cdot, \cdot)$ be a continuous bilinear form over $W \times W$. The problem*

$$\begin{cases} \text{Find } u \in W & \text{such that} \\ \forall v \in W, & \mathcal{A}(u, v) = \ell(v) \end{cases}$$

is well-posed if and only if \mathcal{A} is T-coercive. If so, it holds that

$$\|u\|_W \leq \frac{\|T\|}{\underline{\alpha}} \|\ell\|_{W'}, \tag{4}$$

for all pairs of operators and constants $(T, \underline{\alpha})$ that yield T-coercivity.

Remark 3. In the above definition, we observe that if $(T, \underline{\alpha})$ is a suitable pair, then for all $\lambda > 0$, $(\lambda T, \lambda \underline{\alpha})$ is also a suitable pair. It is then possible to choose a normalized operator T , that is $\|T\| = 1$. In this case, in the proposition, the estimate (4) writes $\|u\|_W \leq \underline{\alpha}^{-1} \|\ell\|_{W'}$.

Remark 4. In [23], the definition and proposition are stated for (possibly) different spaces of solutions u and test functions v .

2.1. *Proving well-posedness with T-coercivity*

With the T-coercivity tool in mind, we are now ready to establish the main result of this section. To that aim, we use the result below, see for instance [33, Corollary I.2.4]. Let $q \in L^2_0(\Omega)$. Then, there exists $\mathbf{v}_q \in \mathbf{H}^1_0(\Omega)$ satisfying

$$-\operatorname{div} \mathbf{v}_q = q. \tag{5}$$

In addition, there exists a constant $C_{\operatorname{div}} > 0$ independent of q such that

$$\|\nabla \mathbf{v}_q\| \leq C_{\operatorname{div}} \|q\|. \tag{6}$$

Theorem 5. *The problem*

$$\begin{cases} \text{Find } (\mathbf{u}, p) \in \mathbf{H}^1_0(\Omega) \times L^2_0(\Omega) \text{ such that} \\ \forall (\mathbf{v}, q) \in \mathbf{H}^1_0(\Omega) \times L^2_0(\Omega), \quad \mathcal{A}((\mathbf{u}, p), (\mathbf{v}, q)) = \langle \mathbf{f}, \mathbf{v} \rangle \end{cases} \tag{7}$$

is well-posed and

$$\|(\mathbf{u}, p)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)} \leq \frac{2 \max(\sqrt{2}vC_{\operatorname{div}}^2, C_{\operatorname{div}}(2 + v^2C_{\operatorname{div}}^2)^{1/2})}{\min(v^2C_{\operatorname{div}}^2, 1)} \|\mathbf{f}\|_{\mathbf{H}^{-1}(\Omega)}. \tag{8}$$

Proof. The linear form defined by

$$\ell((\mathbf{v}, q)) = \langle \mathbf{f}, \mathbf{v} \rangle, \quad \forall (\mathbf{v}, q) \in \mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)$$

is continuous over $\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)$ in view of the inequality

$$\ell((\mathbf{v}, q)) \leq \|\mathbf{f}\|_{\mathbf{H}^{-1}(\Omega)} \|(\mathbf{v}, q)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)}. \tag{9}$$

The bilinear form \mathcal{A} is continuous over $(\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega))^2$ and we observe that it is also symmetric.

Then, from Proposition 2, it is sufficient to show that the bilinear form \mathcal{A} is T-coercive. For a given $(\mathbf{u}, p) \in \mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)$, we look for an element (\mathbf{v}^*, q^*) of $\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)$ depending continuously on (\mathbf{u}, p) and such that

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) \geq \underline{\alpha} \|(\mathbf{u}, p)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)}^2$$

for some constant $\underline{\alpha} > 0$. In order to get an intuitive idea of the construction of (\mathbf{v}^*, q^*) , let us start with specific elements (\mathbf{u}, p) .

- If $p = 0$, then $\|(\mathbf{u}, p)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)}^2 = \|\nabla \mathbf{u}\|^2$ and

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) = v \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v}^* \, dx - \int_{\Omega} \operatorname{div} \mathbf{u} q^* \, dx,$$

so that we can take $\mathbf{v}^* = \mathbf{u}$ and $q^* = p = 0$.

- If $\mathbf{u} = 0$, then $\|(\mathbf{u}, p)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)}^2 = \|p\|^2$ and

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) = - \int_{\Omega} p \operatorname{div} \mathbf{v}^* \, dx.$$

In order to recover the expected term $\|p\|^2$ in the above expression, we have to choose \mathbf{v}^* , the divergence of which is “as close as possible” to $-p$. The idea is now to choose $\mathbf{v}^* = \mathbf{v}_p$, where \mathbf{v}_p is as in (5)-(6). Hence, taking $q^* = 0$, we find

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) = \|p\|^2,$$

and (6) ensures that the pair $(\mathbf{v}_p, 0)$ depends continuously on $(0, p)$ in $\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)$.

- If $\operatorname{div} \mathbf{u} = 0$, then

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) = \nu \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v}^* \, dx - \int_{\Omega} p \operatorname{div} \mathbf{v}^* \, dx.$$

Since we need to get a term of the form $\|\nabla \mathbf{u}\|^2$ but also of the form $\|p\|^2$, we combine the previous two cases by setting $\mathbf{v}^* = \lambda \mathbf{u} + \mathbf{v}_p$, where λ is a positive coefficient to be adjusted and \mathbf{v}_p is the divergence lifting from (5) – (6). Now, we compute

$$\begin{aligned} \mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) &= \nu \lambda \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{u} \, dx + \nu \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v}_p \, dx - \lambda \int_{\Omega} p \operatorname{div} \mathbf{u} \, dx - \int_{\Omega} p \operatorname{div} \mathbf{v}_p \, dx \\ &= \nu \lambda \|\nabla \mathbf{u}\|^2 + \nu \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v}_p \, dx + \|p\|^2 \end{aligned}$$

since $\operatorname{div} \mathbf{u} = 0$ and $-\operatorname{div} \mathbf{v}_p = p$. For all $\eta > 0$, Young’s inequality implies that

$$\begin{aligned} \int_{\Omega} \nabla \mathbf{u} : \nabla \mathbf{v}_p \, dx &\geq -\frac{\eta}{2} \|\nabla \mathbf{u}\|^2 - \frac{1}{2\eta} \|\nabla \mathbf{v}_p\|^2 \\ &\geq -\frac{\eta}{2} \|\nabla \mathbf{u}\|^2 - \frac{C_{\operatorname{div}}^2}{2\eta} \|p\|^2 \quad \text{in virtue of (6),} \end{aligned}$$

and thus

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) \geq \nu \left(\lambda - \frac{\eta}{2} \right) \|\nabla \mathbf{u}\|^2 + \left(1 - \frac{\nu C_{\operatorname{div}}^2}{2\eta} \right) \|p\|^2.$$

Hence, by setting $\eta = \lambda = \nu C_{\operatorname{div}}^2$, we obtain

$$\mathcal{A}((\mathbf{u}, p), (\mathbf{v}^*, q^*)) \geq \frac{\nu^2 C_{\operatorname{div}}^2}{2} \|\nabla \mathbf{u}\|^2 + \frac{1}{2} \|p\|^2.$$

In the general case, we choose $\mathbf{v}^* = \lambda \mathbf{u} + \mathbf{v}_p$ with $\lambda = \nu C_{\operatorname{div}}^2$ and $q^* = -\lambda p$ so that, even if $\operatorname{div} \mathbf{u} \neq 0$, the term $-\lambda \int_{\Omega} p \operatorname{div} \mathbf{u} \, dx$ cancels with the term $-\int_{\Omega} \operatorname{div} \mathbf{u} \, q^* \, dx$ and we get the same results as in the case $\operatorname{div} \mathbf{u} = 0$. Namely, the bilinear form \mathcal{A} is T-coercive for the mapping

$$\begin{aligned} \mathbf{T} : \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega) &\longrightarrow \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega) \\ (\mathbf{u}, p) &\longmapsto (\nu C_{\operatorname{div}}^2 \mathbf{u} + \mathbf{v}_p, -\nu C_{\operatorname{div}}^2 p), \end{aligned}$$

where \mathbf{v}_p is defined by (5) with estimate (6), and it holds that

$$\mathcal{A}((\mathbf{u}, p), \mathbf{T}(\mathbf{u}, p)) \geq \frac{\nu^2 C_{\operatorname{div}}^2}{2} \|\nabla \mathbf{u}\|^2 + \frac{1}{2} \|p\|^2 \geq \frac{1}{2} \min(\nu^2 C_{\operatorname{div}}^2, 1) \|(\mathbf{u}, p)\|_{\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)}^2. \tag{10}$$

Thanks to (5)-(6), \mathbf{T} belongs to $\mathcal{L}(\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega))$. More precisely, we have

$$\begin{aligned} \|\mathbf{T}(\mathbf{u}, p)\|_{\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)}^2 &= \|\nu C_{\operatorname{div}}^2 \mathbf{u} + \mathbf{v}_p\|_{\mathbf{H}_0^1(\Omega)}^2 + \|\nu C_{\operatorname{div}}^2 p\|^2 \\ &\leq 2(\nu C_{\operatorname{div}}^2)^2 \|\nabla \mathbf{u}\|^2 + 2\|\nabla \mathbf{v}_p\|^2 + (\nu C_{\operatorname{div}}^2)^2 \|p\|^2 \\ &\leq 2(\nu C_{\operatorname{div}}^2)^2 \|\nabla \mathbf{u}\|^2 + \left(2C_{\operatorname{div}}^2 + (\nu C_{\operatorname{div}}^2)^2 \right) \|p\|^2 \end{aligned}$$

and thus

$$\|\mathbf{T}\| \leq \max\left(\sqrt{2}\nu C_{\operatorname{div}}^2, C_{\operatorname{div}}(2 + \nu^2 C_{\operatorname{div}}^2)^{1/2}\right). \tag{11}$$

Using (9), (10) and (11) in the stability estimate (4), we finally obtain (8). \square

Remark 6. The previous result readily extends to the case of a non-null divergence constraint

$$\begin{aligned} -\nu \Delta \mathbf{u} + \nabla p &= \mathbf{f}, & \text{in } \Omega, \\ \operatorname{div} \mathbf{u} &= g, & \text{in } \Omega, \\ \mathbf{u} &= 0, & \text{on } \partial\Omega, \end{aligned}$$

with $g \in L^2_0(\Omega)$, leading to the stability estimate

$$\|(\mathbf{u}, p)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)} \leq \frac{2 \max\left(\sqrt{2}\nu C^2_{\text{div}}, C_{\text{div}}(2 + \nu^2 C^2_{\text{div}})^{1/2}\right)}{\min(\nu^2 C^2_{\text{div}}, 1)} \|(\mathbf{f}, g)\|_{\mathbf{H}^{-1}(\Omega) \times L^2_0(\Omega)}. \tag{12}$$

Remark 7. Of course, the all-in-one bilinear form \mathcal{A} can also be studied using Banach–Nečas–Babuška’s theory with inf-sup conditions, see [30, Theorem 49.15 and Lemma 53.12].

2.2. Comments

The stability estimates (8) and (12) are valid for all C_{div} that fulfills (6). On the other hand, one has

$$\lim_{C_{\text{div}} \rightarrow \infty} \frac{2 \max\left(\sqrt{2}\nu C^2_{\text{div}}, C_{\text{div}}(2 + \nu^2 C^2_{\text{div}})^{1/2}\right)}{\min(\nu^2 C^2_{\text{div}}, 1)} = +\infty,$$

i.e. the stability estimates become meaningless for large C_{div} .

Going through the proof of Theorem 5, we observe that the constant obtained in (8) and (12) is just one of the many bounds one can achieve with T-coercivity for the Stokes problem. Indeed, the operator T is in general not unique, see Remark 3. Here, one can choose any positive value of λ , so that there exists a family of admissible operators T in the sense of Definition 1, which shows the flexibility of the approach.

Let us provide an illustration. For small viscosity ν (the domain Ω being fixed), it is well-known that the stability constant appearing in the estimate

$$\|(\mathbf{u}, p)\|_{\mathbf{H}^1_0(\Omega) \times L^2_0(\Omega)} \leq C(\nu) \|(\mathbf{f}, g)\|_{\mathbf{H}^{-1}(\Omega) \times L^2_0(\Omega)}$$

behaves like $O(\nu^{-1})$. For instance, for the velocity \mathbf{u} , the result is elementarily obtained by taking the test field $(\mathbf{v}, q) = (\mathbf{u}, p)$ in (2). On the other hand, in (8) and (12), we find a behavior in $O(\nu^{-2})$. But, if one is interested in obtaining a less severe blowup, one can simply choose

$$\eta = \frac{\nu C^2_{\text{div}}}{2(1 - \frac{\nu}{2})} \quad \text{and} \quad \lambda = \frac{1}{2}(1 + \eta)$$

in the above proof, for all $0 < \nu \leq 1$. Then, one finds that

$$\underline{\alpha} = \frac{\nu}{2} \quad \text{and} \quad \|T\| \leq \max\left(\frac{1}{\sqrt{2}}(1 + C^2_{\text{div}}), \left(2C^2_{\text{div}} + \frac{1}{4}(1 + C^2_{\text{div}})^2\right)^{1/2}\right),$$

so that (4) actually yields a stability constant in $O(\nu^{-1})$.

Theorem 5 provides a constructive proof for the well-posedness of Stokes problem, which is an emblematic example of mixed problem. In the next section, we show that the T-coercivity approach employed here is in fact very general and can be extended to a large class of saddle-point problems.

3. Abstract framework

We start with the classical statements regarding the definition of saddle-point problems, and the equivalent conditions to ensure an inf-sup condition on the constraint. Then, we proceed with the design of abstract operators T to ensure well-posedness for saddle-point problems, and for augmented saddle-point problems.

3.1. Saddle-point problems in Hilbert spaces

Let V and Q be two Hilbert spaces. In the Hilbert space Q , we introduce the canonical isomorphism $\mathbb{1}_{Q \rightarrow Q'} : Q \rightarrow Q'$ defined by

$$\langle \mathbb{1}_{Q \rightarrow Q'} p, q \rangle_{Q', Q} = (p, q)_Q, \quad \forall p \in Q, \forall q \in Q,$$

which is a bijective isometry according to Riesz Theorem. As a matter of fact, its inverse $\mathbb{1}_{Q' \rightarrow Q}$ is also a bijective isometry, and

$$(\mathbb{1}_{Q' \rightarrow Q} g, q)_Q = \langle g, q \rangle_{Q', Q}, \quad \forall g \in Q', \forall q \in Q.$$

We then introduce two bilinear forms $a(\cdot, \cdot)$ on $V \times V$ and $b(\cdot, \cdot)$ on $V \times Q$ that are assumed to be continuous, i.e. there exist $C_a > 0$ and $C_b > 0$ such that

$$a(u, v) \leq C_a \|u\|_V \|v\|_V, \quad \forall u \in V, \forall v \in V, \quad (13)$$

$$b(v, q) \leq C_b \|v\|_V \|q\|_Q, \quad \forall v \in V, \forall q \in Q. \quad (14)$$

We denote by A and B the linear continuous operators associated with a and b , defined by

$$A \in \mathcal{L}(V, V'), \quad \langle Au, v \rangle_{V', V} = a(u, v), \quad \forall u \in V, \forall v \in V,$$

$$B \in \mathcal{L}(V, Q'), \quad \langle Bv, q \rangle_{Q', Q} = b(v, q), \quad \forall v \in V, \forall q \in Q.$$

The adjoint operator of B is given by

$$B^* \in \mathcal{L}(Q, V'), \quad \langle B^* q, v \rangle_{V', V} = \langle Bv, q \rangle_{Q', Q} = b(v, q), \quad \forall v \in V, \forall q \in Q.$$

Given $f \in V'$ and $g \in Q'$, we consider the saddle-point problem: find $(u, p) \in V \times Q$ such that

$$\begin{aligned} Au + B^* p &= f, & \text{in } V', \\ Bu &= g, & \text{in } Q'. \end{aligned} \quad (15)$$

Or, equivalently, in variational form:

$$\begin{cases} \text{Find } (u, p) \in V \times Q & \text{such that} \\ \forall v \in V, & a(u, v) + b(v, p) = \langle f, v \rangle_{V', V}, \\ \forall q \in Q, & b(u, q) = \langle g, q \rangle_{Q', Q}. \end{cases} \quad (16)$$

As for the Stokes problem, we write Problem (15) as an *all-in-one* variational formulation

$$\begin{cases} \text{Find } (u, p) \in V \times Q & \text{such that} \\ \forall (v, q) \in V \times Q, & \mathcal{A}((u, p), (v, q)) = \langle f, v \rangle_{V', V} + \langle g, q \rangle_{Q', Q}, \end{cases} \quad (17)$$

where

$$\mathcal{A}((u, p), (v, q)) = a(u, v) + b(v, p) + b(u, q).$$

In what follows, we show that Problem (17) is well-posed using the notion of T-coercivity, with slightly different techniques depending on the assumptions on the bilinear form a .

Regarding the form $b(\cdot, \cdot)$ and the operator B , one has the well-known result below, see for instance [33, Lemma I.4.1]¹ or [30, Lemma C.44], which can be viewed as a reformulation of Banach's Closed Range Theorem.

Theorem 8. *The following three statements are equivalent:*

(i) *There exists $\underline{\beta} > 0$ such that*

$$\inf_{q \in Q \setminus \{0\}} \sup_{v \in V \setminus \{0\}} \frac{b(v, q)}{\|v\|_V \|q\|_Q} \geq \underline{\beta}. \quad (18)$$

¹Item (iii) below is a rephrasing of the original statement, because it is better suited for our purposes. For details, see the proof of [33, Lemma I.4.1, p. 59, item 2]. The operator L_B is a *right-inverse* of the operator B .

(ii) $B : (\text{Ker } B)^\perp \rightarrow Q'$ is an isomorphism, and

$$\|Bv\|_{Q'} \geq \underline{\beta} \|v\|_V, \quad \forall v \in (\text{Ker } B)^\perp.$$

(iii) There exists an isomorphic operator $L_B : Q' \rightarrow (\text{Ker } B)^\perp$ such that

$$B(L_B g) = g \quad \text{and} \quad \|g\|_{Q'} \geq \underline{\beta} \|L_B g\|_V, \quad \forall g \in Q'.$$

Since our aim is to build operators T from $V \times Q$ to itself, we first introduce the operator

$$B = \mathbb{1}_{Q' \rightarrow Q} \circ B : V \rightarrow Q.$$

For all $v \in V$, $\|Bv\|_{Q'} = \|\mathbb{1}_{Q' \rightarrow Q}(Bv)\|_Q = \|Bv\|_Q$ and, for all $(v, q) \in V \times Q$,

$$b(v, q) = \langle Bv, q \rangle_{Q', Q} = \langle \mathbb{1}_{Q' \rightarrow Q}(Bv), q \rangle_{Q', Q} = (Bv, q)_Q. \tag{19}$$

Whenever applicable, we also introduce its *right-inverse*

$$L_B = L_B \circ \mathbb{1}_{Q \rightarrow Q'} : Q \rightarrow (\text{Ker } B)^\perp.$$

Observe that

$$b(L_B p, q) = \langle BL_B p, q \rangle_{Q', Q} = \langle \mathbb{1}_{Q' \rightarrow Q} p, q \rangle_{Q', Q} = (p, q)_Q, \quad \forall p \in Q, \forall q \in Q. \tag{20}$$

Under these notations, items (ii)-(iii) of Theorem 8 now write

(i) $B : (\text{Ker } B)^\perp \rightarrow Q$ is an *isomorphism*, and

$$\|Bv\|_Q \geq \underline{\beta} \|v\|_V, \quad \forall v \in (\text{Ker } B)^\perp. \tag{21}$$

(ii) There exists an isomorphic operator $L_B : Q \rightarrow (\text{Ker } B)^\perp$ such that

$$B(L_B q) = q \quad \text{and} \quad \|q\|_Q \geq \underline{\beta} \|L_B q\|_V, \quad \forall q \in Q. \tag{22}$$

For convenience, we often use $\beta = \underline{\beta}^{-1}$, so that

$$\|L_B q\|_V \leq \beta \|q\|_Q, \quad \forall q \in Q.$$

3.2. How to achieve T -coercivity for saddle-point problems?

If a is coercive on the whole space V , we can extend the proof of Theorem 5 in the following way.

Theorem 9. Assume that the inf-sup condition (18) on the form b holds true and that the form a is symmetric and positive. If there exists a constant $\alpha > 0$ such that

$$a(u, u) \geq \alpha \|u\|_V^2, \quad \forall u \in V, \tag{23}$$

then there exists a unique solution to Problem (17) and

$$\|(u, p)\|_{V \times Q} \leq \frac{2 \max\left(\sqrt{2} C_a \beta^2, \beta(2 + C_a^2 \beta^2)^{1/2}\right)}{\min(\alpha C_a \beta^2, 1)} \|(f, g)\|_{V' \times Q'}. \tag{24}$$

Proof. First, we note that the symmetry of the bilinear form a implies that \mathcal{A} is also symmetric. Then, we follow the same ideas as in the proof of Theorem 5, replacing v_p by $L_B p$. We introduce the mapping

$$\begin{aligned} T : V \times Q &\longrightarrow V \times Q \\ (u, p) &\longmapsto (\lambda u + L_B p, -\lambda p) \end{aligned}$$

and we compute

$$\begin{aligned} \mathcal{A}((u, p), T(u, p)) &= a(u, \lambda u) + a(u, L_B p) + b(\lambda u, p) + b(L_B p, p) - b(u, \lambda p) \\ &= \lambda a(u, u) + a(u, L_B p) + \|p\|_Q^2, \end{aligned}$$

in view of (20).

Because the form a is symmetric and positive, we can apply Young’s inequality: for any $\eta > 0$,

$$a(u, L_B p) \geq -\frac{\eta}{2} a(u, u) - \frac{1}{2\eta} a(L_B p, L_B p).$$

Taking into account (13) and (22), the latter being equivalent to (18), we get

$$a(L_B p, L_B p) \leq C_a \|L_B p\|_V^2 \leq C_a \beta^2 \|p\|_Q^2$$

and thus

$$a(u, L_B p) \geq -\frac{\eta}{2} a(u, u) - \frac{C_a \beta^2}{2\eta} \|p\|_Q^2.$$

Hence, recalling (23), if $\lambda - \frac{\eta}{2} > 0$ it follows that

$$\mathcal{A}((u, p), T(u, p)) \geq \alpha \left(\lambda - \frac{\eta}{2} \right) \|u\|_V^2 + \left(1 - \frac{C_a \beta^2}{2\eta} \right) \|p\|_Q^2.$$

Setting in particular $\eta = \lambda = C_a \beta^2$, we infer that

$$\mathcal{A}((u, p), T(u, p)) \geq \alpha \frac{C_a \beta^2}{2} \|u\|_V^2 + \frac{1}{2} \|p\|_Q^2 \geq \frac{1}{2} \min(\alpha C_a \beta^2, 1) \|(u, p)\|_{V \times Q}^2, \tag{25}$$

which proves that \mathcal{A} is T-coercive.

Since $T(u, p) = (C_a \beta^2 u + L_B p, -C_a \beta^2 p)$, it holds that

$$\begin{aligned} \|T(u, p)\|_{V \times Q}^2 &= \|C_a \beta^2 u + L_B p\|_V^2 + \|C_a \beta^2 p\|_Q^2 \\ &\leq 2(C_a \beta^2)^2 \|u\|_V^2 + 2\|L_B p\|_V^2 + (C_a \beta^2)^2 \|p\|_Q^2 \\ &\leq 2(C_a \beta^2)^2 \|u\|_V^2 + (2\beta^2 + (C_a \beta^2)^2) \|p\|_Q^2, \end{aligned}$$

which yields

$$\|T\| \leq \max\left(\sqrt{2} C_a \beta^2, \beta(2 + C_a^2 \beta^2)^{1/2}\right). \tag{26}$$

Lastly, we observe that

$$\langle f, v \rangle_{V', V} + \langle g, q \rangle_{Q', Q} \leq \|(f, g)\|_{V' \times Q'} \|(v, q)\|_{V \times Q}. \tag{27}$$

Combining (25), (26) and (27), the stability estimate (4) furnishes exactly (24). \square

Remark 10. By applying Theorem 9 to Stokes problem, we recover stability estimates (8) and (12) from the correspondence $\alpha = \nu$, $C_a = \nu$ and $\beta = C_{\text{div}}$.

In Ladyzhenskaya–Babuška–Brezzi’s theory and in many applications, the bilinear form a is not coercive on the whole space V but only on the kernel of the operator B . This is for instance the case in electromagnetism, which will be detailed in Section 4. The next result shows how to address this situation in the T-coercivity framework (provided that the form a is symmetric and positive), thus establishing the equivalence between the two theories.

Theorem 11. *Assume that the form a is symmetric and positive.*

- (1) *If the inf-sup condition (18) on the form b holds true, and if there exists a constant $\alpha_0 > 0$ such that*

$$a(u_0, u_0) \geq \alpha_0 \|u_0\|_V^2, \quad \forall u_0 \in \text{Ker } B, \tag{28}$$

then the form \mathcal{A} is T-coercive. In other words, Problem (17) is well-posed and

$$\|(u, p)\|_{V \times Q} \leq C \|(f, g)\|_{V' \times Q'}, \tag{29}$$

with C a constant depending only on α_0 , β , C_a and C_b .

- (2) *Conversely, if Problem (17) is well-posed, that is, if the form \mathcal{A} is T-coercive, then (18) and (28) both hold.*

Proof. (1) We consider the mapping

$$\begin{aligned} T: V \times Q &\longrightarrow V \times Q \\ (u, p) &\longmapsto (\lambda u + L_B p, -\lambda p + \lambda \mu B u). \end{aligned}$$

This is almost the same mapping as the one used in the proof of Theorem 9. The only difference is the term $\lambda \mu B u$, which is going to help us handling the extra terms that do not belong to the kernel of B by adjusting the value of the constant μ . We get

$$\begin{aligned} \mathcal{A}((u, p), T(u, p)) &= a(u, \lambda u) + a(u, L_B p) + b(\lambda u, p) + b(L_B p, p) - b(u, \lambda p) + b(u, \lambda \mu B u) \\ &= \lambda a(u, u) + a(u, L_B p) + \|p\|_Q^2 + \lambda \mu \|B u\|_Q^2 \end{aligned}$$

because $b(L_B p, p) = \|p\|_Q^2$ as previously, and

$$b(u, B u) = \langle B u, B u \rangle_{Q', Q} = (\mathbb{1}_{Q' \rightarrow Q}(B u), B u)_Q = \|B u\|_Q^2.$$

Since the form a is symmetric and positive, one may use Young's inequality. By proceeding as in the proof of Theorem 9 and after setting $\lambda = C_a \beta^2$, we know that

$$\lambda a(u, u) + a(u, L_B p) + \|p\|_Q^2 \geq \frac{C_a \beta^2}{2} a(u, u) + \frac{1}{2} \|p\|_Q^2,$$

from which we deduce

$$\mathcal{A}((u, p), T(u, p)) \geq \frac{C_a \beta^2}{2} (a(u, u) + 2\mu \|B u\|_Q^2) + \frac{1}{2} \|p\|_Q^2.$$

To compensate the lack of coercivity of a outside $\text{Ker} B$, we use the decomposition $u = u_0 + \bar{u}$ with $u_0 \in \text{Ker} B$ and $\bar{u} \in (\text{Ker} B)^\perp$. Following [5, p. 254], Young's inequality yields

$$\begin{aligned} a(u, u) &= a(u_0, u_0) + 2a(u_0, \bar{u}) + a(\bar{u}, \bar{u}) \\ &\geq (1 - \theta) a(u_0, u_0) + \left(1 - \frac{1}{\theta}\right) a(\bar{u}, \bar{u}) \\ &\geq (1 - \theta) a(u_0, u_0) + \left(C_a - \frac{C_a}{\theta}\right) \|\bar{u}\|_V^2 \end{aligned}$$

for all $0 < \theta < 1$. Since $u_0 \in \text{Ker} B$, we have $\|B u\|_Q^2 = \|B \bar{u}\|_Q^2$. Moreover, using (21) yields $\|B \bar{u}\|_Q^2 \geq \beta^{-2} \|\bar{u}\|_V^2$. Thus

$$a(u, u) + 2\mu \|B u\|_Q^2 \geq (1 - \theta) a(u_0, u_0) + \left(C_a - \frac{C_a}{\theta} + \frac{2\mu}{\beta^2}\right) \|\bar{u}\|_V^2. \tag{30}$$

Choosing $\theta = \frac{1}{2}$ and $\mu = \frac{3}{4} C_a \beta^2$, it holds that

$$a(u, u) + 2\mu \|B u\|_Q^2 \geq \frac{1}{2} a(u_0, u_0) + \frac{C_a}{2} \|\bar{u}\|_V^2.$$

Hence, recalling (28) and using the inequality $C_a \geq \alpha_0$, we obtain

$$a(u, u) + 2\mu \|B u\|_Q^2 \geq \frac{\alpha_0}{2} \|u_0\|_V^2 + \frac{\alpha_0}{2} \|\bar{u}\|_V^2 = \frac{\alpha_0}{2} \|u\|_V^2$$

and we conclude that

$$\mathcal{A}((u, p), T(u, p)) \geq \alpha_0 \frac{C_a \beta^2}{4} \|u\|_V^2 + \frac{1}{2} \|p\|_Q^2. \tag{31}$$

From the above, we have

$$T(u, p) = (C_a \beta^2 u + L_B p, -C_a \beta^2 p + \frac{3}{4} (C_a \beta^2)^2 B u).$$

Finally, T belongs to $\mathcal{L}(V \times Q)$ since $\|L_B p\|_V \leq \beta \|p\|_Q$ (see (22)) and²

$$\|Bu\|_Q \leq C_b \|u\|_V. \tag{32}$$

The stability estimate (29) is then given by (4).

(2) Conversely, suppose that there exist $\alpha_V > 0$, $\alpha_Q > 0$ and $T \in \mathcal{L}(V \times Q)$ such that

$$\mathcal{A}((u, p), T(u, p)) \geq \alpha_V \|u\|_V^2 + \alpha_Q \|p\|_Q^2, \quad \forall (u, p) \in V \times Q. \tag{33}$$

Noting $T : (u, p) \mapsto (T_V(u, p), T_Q(u, p))$, we have

$$\mathcal{A}((u, p), T(u, p)) = a(u, T_V(u, p)) + b(T_V(u, p), p) + b(u, T_Q(u, p))$$

and, since T is bounded,

$$\|T_V(u, p)\|_V^2 + \|T_Q(u, p)\|_Q^2 \leq \|T\|^2 (\|u\|_V^2 + \|p\|_Q^2). \tag{34}$$

Now, choosing $u = 0$ in (33) and (34) yields

$$b(T_V(0, p), p) \geq \alpha_Q \|p\|_Q^2 \quad \text{and} \quad \|T_V(0, p)\|_V \leq \|T\| \|p\|_Q, \quad \forall p \in Q.$$

Thus, for $p \in Q \setminus \{0\}$, $T_V(0, p) \neq 0$, otherwise $b(T_V(0, p), p) = 0$, which contradicts $b(T_V(0, p), p) > 0$. Then it follows that

$$\sup_{v \in V \setminus \{0\}} \frac{b(v, p)}{\|v\|_V} \geq \frac{b(T_V(0, p), p)}{\|T_V(0, p)\|_V} \geq \frac{\alpha_Q}{\|T\|} \|p\|_Q, \quad \forall p \in Q \setminus \{0\},$$

which shows that the inf-sup condition (18) is fulfilled. Likewise, taking $p = 0$ and $u \in \text{Ker} B$ in (33) and (34), we get

$$a(u, T_V(u, 0)) \geq \alpha_V \|u\|_V^2 \quad \text{and} \quad \|T_V(u, 0)\|_V \leq \|T\| \|u\|_V, \quad \forall u \in \text{Ker} B.$$

By symmetry and positivity of a , it holds that

$$a(u, T_V(u, 0)) \leq (a(u, u))^{1/2} a(T_V(u, 0), T_V(u, 0))^{1/2}.$$

Thus

$$\alpha_V \|u\|_V^2 \leq a(u, T_V(u, 0)) \leq (a(u, u))^{1/2} (C_a \|T\|^2 \|u\|_V^2)^{1/2}$$

and hence $a(u, u) \geq \frac{\alpha_V^2}{C_a \|T\|^2} \|u\|_V^2$ for all $u \in \text{Ker} B$, which proves (28). □

Remark 12. The T -coercivity estimate (31) is very close to the case where a is coercive on the whole space V . As a matter of fact, the only difference compared to (25) is that the constant before the term $\|u\|_V^2$ is twice as small, with $\alpha_0 = \alpha$.

² Classically,

$$\begin{aligned} \|Bu\|_Q^2 &= (Bu, Bu)_Q = \langle \mathbb{1}_{Q \rightarrow Q'}(Bu), Bu \rangle_{Q', Q} \quad \text{by definition of } \mathbb{1}_{Q \rightarrow Q'}, \\ &= \langle \mathbb{1}_{Q \rightarrow Q'} \circ \mathbb{1}_{Q' \rightarrow Q}(Bu), Bu \rangle_{Q', Q} = (Bu, Bu)_{Q', Q} \quad \text{since } \mathbb{1}_{Q \rightarrow Q'} \circ \mathbb{1}_{Q' \rightarrow Q} = \text{Id}_{Q'}, \\ &= b(u, Bu) \leq C_b \|u\|_V \|Bu\|_Q \quad \text{by definition and continuity of } b \text{ (14)}. \end{aligned}$$

3.3. Augmented saddle-point problems

Let $c(\cdot, \cdot)$ be a positive and continuous bilinear form defined on $Q \times Q$, namely

$$c(p, p) \geq 0, \quad \forall p \in Q \quad \text{and} \quad \exists C_c > 0, \quad c(p, q) \leq C_c \|p\|_Q \|q\|_Q, \quad \forall p \in Q, \forall q \in Q. \quad (35)$$

In some cases, the assumption on the positivity of the form c can be relaxed, see Remark 14. We denote by C the linear operator associated with the form c , defined by

$$C \in \mathcal{L}(Q, Q'), \quad \langle Cp, q \rangle_{Q', Q} = c(p, q), \quad \forall p \in Q, \forall q \in Q.$$

The *all-in-one* approach developed previously also enables us to deal with augmented saddle-point problems: given $f \in V'$ and $g \in Q'$, find $(u, p) \in V \times Q$ such that

$$\begin{aligned} Au + B^*p &= f, & \text{in } V', \\ Bu - Cp &= g, & \text{in } Q', \end{aligned} \quad (36)$$

where the operator C possibly acts as a *small perturbation* of the original saddle-point problem (15). The weak formulation of (36) reads:

$$\begin{cases} \text{Find } (u, p) \in V \times Q \text{ such that} \\ \forall (v, q) \in V \times Q, \quad \mathcal{A}_c((u, p), (v, q)) = \langle f, v \rangle_{V', V} + \langle g, q \rangle_{Q', Q}, \end{cases} \quad (37)$$

with

$$\mathcal{A}_c((u, p), (v, q)) = a(u, v) + b(v, p) + b(u, q) - c(p, q).$$

As before, the bilinear form a is supposed to be symmetric and positive.

3.4. How to achieve T-coercivity for augmented saddle-point problems?

Once again, we distinguish the case where the form a is coercive on V or only on $\text{Ker} B$. If the form a is coercive on V , the results from the un-augmented case allow straightforwardly to handle the augmented one.

Theorem 13. *Assume that the inf-sup condition (18) on the form b holds true, that the form c fulfills (35) and that the form a is symmetric and positive. If there exists a constant $\alpha > 0$ such that*

$$a(u, u) \geq \alpha \|u\|_V^2, \quad \forall u \in V,$$

then there exists a unique solution to Problem (37).

Proof. With the same operator T as for the un-augmented problem, namely

$$\begin{aligned} T: V \times Q &\longrightarrow V \times Q \\ (u, p) &\longmapsto (C_a \beta^2 u + L_B p, -C_a \beta^2 p), \end{aligned}$$

it holds that

$$\mathcal{A}_c((u, p), T(u, p)) = C_a \beta^2 a(u, u) + a(u, L_B p) + \|p\|_Q^2 + C_a \beta^2 c(p, p).$$

Therefore, a similar argument as in Theorem 9 furnishes

$$\mathcal{A}_c((u, p), T(u, p)) \geq \alpha \frac{C_a \beta^2}{2} \|u\|_V^2 + \frac{1}{2} \|p\|_Q^2 + C_a \beta^2 c(p, p),$$

which shows that \mathcal{A}_c is T-coercive since c is positive. □

Remark 14. A particular case that appears in many applications – see Section 5 for the example of nearly-incompressible elasticity – is when c has the form

$$c(p, q) = \varepsilon(p, q)_Q, \quad \varepsilon \geq 0.$$

In this case, we obtain the estimate

$$\mathcal{A}_c((u, p), T(u, p)) \geq \alpha \frac{C_a \beta^2}{2} \|u\|_V^2 + \left(\frac{1}{2} + \varepsilon C_a \beta^2\right) \|p\|_Q^2, \tag{38}$$

so that the augmentation c improves the constant before the term $\|p\|_Q^2$ and thus stabilizes the bilinear form \mathcal{A}_c . Moreover, the above estimate is robust for small values of ε . Besides, it even allows to take negative values of ε . Indeed, if $\varepsilon < 0$, we have

$$\mathcal{A}_c((u, p), T(u, p)) \geq \alpha \frac{C_a \beta^2}{2} \|u\|_V^2 + \left(\frac{1}{2} - |\varepsilon| C_a \beta^2\right) \|p\|_Q^2.$$

Hence, the bilinear form \mathcal{A}_c remains T-coercive whenever $|\varepsilon| < \frac{1}{2C_a \beta^2}$.

Let us now suppose that a is not coercive on the whole space V but only on the kernel of B . Then, two different situations occur. Either the form c can be viewed as a *small perturbation*, and we shall look for a solution of (36) that is *close* to the solution of the original problem (15). Or this is not the case, and the form c is viewed as a “fixed” augmentation, and there is no obvious connection a priori between the solutions of the augmented and un-augmented problems.

3.5. Additional results for small perturbations

We say that c is a small perturbation if it can be written as

$$c(p, q) = \varepsilon c_0(p, q), \quad \varepsilon > 0, \tag{39}$$

with ε a small parameter and c_0 a symmetric, positive and continuous form on Q . We start with the simple case

$$c(p, q) = \varepsilon(p, q)_Q, \quad \varepsilon > 0, \tag{40}$$

for which the T-coercivity approach yields a shorter proof than the corresponding result stated in Ladyzhenskaya–Babuška–Brezzi’s framework, see [5, p. 247-252].

Theorem 15. *Assume that the inf-sup condition (18) on the form b holds true, that the form a is symmetric and positive, and that c takes the simple form of (40). If there exists a constant $\alpha_0 > 0$ such that*

$$a(u_0, u_0) \geq \alpha_0 \|u_0\|_V^2, \quad \forall u_0 \in \text{Ker } B, \tag{41}$$

and if ε is small enough, namely

$$\varepsilon \leq \frac{1}{2C_a \beta^4 C_b^2} \left(2 - \frac{\alpha_0}{C_a}\right), \tag{42}$$

then Problem (37) is well-posed and

$$\|(u, p)\|_{V \times Q} \leq C \|(f, g)\|_{V' \times Q'}, \tag{43}$$

with C a constant depending only on α_0, β, C_a and C_b .

Proof. Here again, we consider the mapping

$$\begin{aligned} T: V \times Q &\longrightarrow V \times Q \\ (u, p) &\longmapsto (\lambda u + L_B p, -\lambda p + \lambda \mu B u). \end{aligned}$$

The beginning of the proof is the same as in Theorem 11. Taking into account the extra terms coming from the perturbation, we get

$$\mathcal{A}_c((u, p), T(u, p)) = \lambda a(u, u) + a(u, L_B p) + \|p\|_Q^2 + \lambda \mu \|B u\|_Q^2 + \lambda c(p, p) - \lambda \mu c(p, B u).$$

Using Young’s inequality and setting $\lambda = C_a\beta^2$, it follows that

$$\mathcal{A}_c((u, p), T(u, p)) \geq \frac{C_a\beta^2}{2} (a(u, u) + 2\mu \|Bu\|_Q^2) + \frac{1}{2} \|p\|_Q^2 + C_a\beta^2 c(p, p) - C_a\beta^2 \mu c(p, Bu). \quad (44)$$

Now, as in (30), it holds that

$$a(u, u) + 2\mu \|Bu\|_Q^2 \geq (1 - \theta) a(u_0, u_0) + \left(C_a - \frac{C_a}{\theta} + \frac{2\mu}{\beta^2}\right) \|\bar{u}\|_V^2 \quad (45)$$

for all $0 < \theta < 1$, where $u = u_0 + \bar{u}$ with $u_0 \in \text{Ker} B$ and $\bar{u} \in (\text{Ker} B)^\perp$.

Knowing that $c(p, q) = \varepsilon(p, q)_Q$ for all p and q in Q , Young’s inequality implies that, for all $\delta > 0$,

$$\begin{aligned} -c(p, Bu) &= -c(p, B\bar{u}) = -\varepsilon(p, B\bar{u})_Q \geq -\varepsilon \frac{\delta}{2} \|p\|_Q^2 - \frac{\varepsilon}{2\delta} \|B\bar{u}\|_Q^2 \\ &\geq -\varepsilon \frac{\delta}{2} \|p\|_Q^2 - \varepsilon \frac{C_b^2}{2\delta} \|\bar{u}\|_V^2 \quad \text{in view of (32)}. \end{aligned}$$

Putting (44), (45) and the above inequality together, we find that

$$\begin{aligned} \mathcal{A}_c((u, p), T(u, p)) &\geq \frac{C_a\beta^2}{2} \left((1 - \theta) a(u_0, u_0) + \left(C_a - \frac{C_a}{\theta} + \frac{2\mu}{\beta^2} - \mu\varepsilon \frac{C_b^2}{\delta}\right) \|\bar{u}\|_V^2 \right) \\ &\quad + \frac{1}{2} \|p\|_Q^2 + \varepsilon C_a\beta^2 \left(1 - \mu \frac{\delta}{2}\right) \|p\|_Q^2. \end{aligned}$$

Hence, choosing $\theta = \frac{1}{2}$, $\mu = C_a\beta^2$ and recalling (41), it holds that

$$\begin{aligned} \mathcal{A}_c((u, p), T(u, p)) &\geq \frac{C_a\beta^2}{2} \left(\frac{\alpha_0}{2} \|u_0\|_V^2 + C_a \left(1 - \varepsilon \frac{\beta^2 C_b^2}{\delta}\right) \|\bar{u}\|_V^2 \right) + \frac{1}{2} \|p\|_Q^2 + \varepsilon C_a\beta^2 \left(1 - C_a\beta^2 \frac{\delta}{2}\right) \|p\|_Q^2. \quad (46) \end{aligned}$$

Finally, we set $\delta = \frac{1}{C_a\beta^2}$ so that

$$1 - C_a\beta^2 \frac{\delta}{2} = \frac{1}{2} \quad \text{and} \quad 1 - \varepsilon \frac{\beta^2 C_b^2}{\delta} = 1 - \varepsilon C_a\beta^4 C_b^2 \geq \frac{1}{2} \cdot \frac{\alpha_0}{C_a}$$

in virtue of (42). Thus

$$\mathcal{A}_c((u, p), T(u, p)) \geq \alpha_0 \frac{C_a\beta^2}{4} \|u\|_V^2 + \left(\frac{1}{2} + \varepsilon \frac{C_a\beta^2}{2}\right) \|p\|_Q^2, \quad (47)$$

where we used that $\|u\|_V^2 = \|u_0\|_V^2 + \|\bar{u}\|_V^2$. All in all, we have chosen

$$T(u, p) = (C_a\beta^2 u + L_B p, -C_a\beta^2 p + (C_a\beta^2)^2 Bu).$$

Then, estimate (43) follows from (4) with a stability constant independent of ε since (47) is robust for vanishing ε and since $\|T\|$ does not depend on ε either. \square

Remark 16. The final estimate (47) is very close to (38). The only difference between these two estimates is a factor of 2 between the constants multiplying the norms of u and p , with $\alpha_0 = \alpha$.

Remark 17. In Ladyzhenskaya–Babuška–Brezzi’s framework, it is commonly assumed that $\varepsilon \leq 1$. On the other hand, in (42), we find a smallness condition that depends *explicitly* on the various constants of the problem.

Remark 18. The inf-sup condition (18) and the continuity of b imply that $\underline{\beta} \leq C_b$, i.e. $C_b\beta \geq 1$. Therefore, (42) yields in particular

$$\varepsilon \leq \frac{1}{C_a\beta^2},$$

which corresponds to the condition found in Remark 14 for negative values of ε . As a matter of fact, the non-coercivity of a on the whole space V calls for the introduction of a term Bu in

the mapping T . This term induces an additional term of the form $c(p, Bu)$ in the expression of $\mathcal{A}_c((u, p), T(u, p))$, that can be interpreted as a “negative perturbation” of the bilinear form \mathcal{A} .

Now, we move to the case where c is given by (39). Let us denote by C_{c_0} the continuity constant of the bilinear form c_0 . The next theorem establishes the well-posedness of the perturbed problem for a very general form c_0 .

Theorem 19. *Assume that the inf-sup condition (18) on the form b holds true, and that the bilinear forms a and c_0 are both symmetric and positive and that c takes the form (39). Suppose in addition that there exists $\alpha_0 > 0$ such that*

$$a(u_0, u_0) \geq \alpha_0 \|u_0\|_V^2, \quad \forall u_0 \in \text{Ker } B.$$

If ε is small enough, namely

$$\varepsilon \leq \frac{1}{2C_{c_0} C_a \beta^4 C_b^2}, \tag{48}$$

then Problem (37) is well-posed and

$$\|(u, p)\|_{V \times Q} \leq C \|(f, g)\|_{V' \times Q'},$$

with C a constant depending only on α_0, β, C_a and C_b .

Proof. First, we adapt the beginning of the proof of Theorem 15 to take into consideration the bilinear form c_0 . Since c_0 is symmetric and positive, we can use Young’s inequality to obtain

$$\begin{aligned} -c(p, Bu) &= -\varepsilon c_0(p, B\bar{u})_Q \geq -\varepsilon \frac{\delta}{2} c_0(p, p) - \frac{\varepsilon}{2\delta} c_0(B\bar{u}, B\bar{u}) \\ &\geq -\varepsilon \frac{\delta}{2} c_0(p, p) - \varepsilon \frac{C_{c_0} C_b^2}{2\delta} \|\bar{u}\|_V^2 \quad \text{since } \|B\bar{u}\|_Q^2 \leq C_b^2 \|\bar{u}\|_V^2, \end{aligned}$$

and thus (46) becomes

$$\begin{aligned} \mathcal{A}_c((u, p), T(u, p)) &\geq \frac{C_a \beta^2}{2} \left(\frac{\alpha_0}{2} \|u_0\|_V^2 + C_a \left(1 - \varepsilon \frac{C_{c_0} \beta^2 C_b^2}{\delta} \right) \|\bar{u}\|_V^2 \right) \\ &\quad + \frac{1}{2} \|p\|_Q^2 + \varepsilon C_a \beta^2 \left(1 - C_a \beta^2 \frac{\delta}{2} \right) c_0(p, p), \end{aligned}$$

where T is the mapping

$$\begin{aligned} T: V \times Q &\longrightarrow V \times Q \\ (u, p) &\longmapsto (C_a \beta^2 u + L_B p, -C_a \beta^2 p + (C_a \beta^2)^2 B u). \end{aligned}$$

Setting $\delta = \frac{1}{C_a \beta^2}$ as before, we get the estimate

$$\mathcal{A}_c((u, p), T(u, p)) \geq \alpha_0 \frac{C_a \beta^2}{4} \|u\|_V^2 + \frac{1}{2} \|p\|_Q^2 + \varepsilon \frac{C_a \beta^2}{2} c_0(p, p),$$

as long as $\varepsilon \leq \frac{1}{2C_{c_0} C_a \beta^4 C_b^2} (2 - \frac{\alpha_0}{C_a})$, which is the case under the assumption (48) since $\alpha_0 \leq C_a$.

Because the bilinear form c_0 is positive, this shows that \mathcal{A}_c is T -coercive. □

Lastly, we mention that an important consequence of the previous result is to estimate the distance between the solution $(u_\varepsilon, p_\varepsilon)$ of the perturbed problem

$$\begin{aligned} Au_\varepsilon + B^* p_\varepsilon &= f, \quad \text{in } V', \\ Bu_\varepsilon - \varepsilon C_0 p_\varepsilon &= g, \quad \text{in } Q', \end{aligned} \tag{49}$$

and the solution (u, p) of the original saddle-point problem (15) as a function of the penalty parameter ε .

Corollary 20. Assume that the inf-sup condition (18) on the form b holds true, that the forms a and c_0 are symmetric and positive, and that c takes the form of (39). If there exists $\alpha_0 > 0$ such that

$$a(u_0, u_0) \geq \alpha_0 \|u_0\|_V^2, \quad \forall u_0 \in \text{Ker} B,$$

and if

$$\varepsilon \leq \frac{1}{2C_{c_0} C_a \beta^4 C_b^2},$$

then we have

$$\|u - u_\varepsilon\|_V + \|p - p_\varepsilon\|_Q \leq C\varepsilon, \tag{50}$$

with C a constant depending only on $\alpha_0, \beta, C_a, C_b$ and C_{c_0} .

Proof. Subtracting (49) from (15), we find that $(u - u_\varepsilon, p - p_\varepsilon)$ solves the system

$$\begin{aligned} A(u - u_\varepsilon) + B^*(p - p_\varepsilon) &= 0, & \text{in } V', \\ B(u - u_\varepsilon) - \varepsilon C_0(p - p_\varepsilon) &= -\varepsilon C_0 p, & \text{in } Q'. \end{aligned}$$

From Theorem 19, we infer that

$$\|(u - u_\varepsilon, p - p_\varepsilon)\|_{V \times Q} \leq C \|(0, -\varepsilon C_0 p)\|_{V' \times Q'}$$

with C depending only on α_0, β, C_a and C_b . Thus

$$\|(u - u_\varepsilon, p - p_\varepsilon)\|_{V \times Q} \leq C C_{c_0} \varepsilon \|p\|_Q,$$

which proves (50). □

3.6. Case of a “fixed” augmentation

If the bilinear form c is not given by (39), the extra terms of the form $c(p, Bu)$ arising from the previously considered T-coercivity operator cannot be controlled as before, because there is no factor ε to adjust. Below, we assume that c is coercive on Q , namely that there exists $\gamma > 0$ such that

$$c(p, p) \geq \gamma \|p\|_Q^2, \quad \forall p \in Q. \tag{51}$$

So, to control these extra terms, we introduce an operator C^{-1} in the expression of T, where $C^{-1} \in \mathcal{L}(Q', Q)$ is defined by

$$c(C^{-1}g, q) = \langle g, q \rangle_{Q', Q}, \quad \forall g \in Q', \forall q \in Q.$$

One can easily check that the operator C^{-1} satisfies

$$(C_c)^{-1} \|g\|_{Q'} \leq \|C^{-1}g\|_Q \leq \gamma^{-1} \|g\|_{Q'}, \quad \forall g \in Q',$$

and

$$\langle g, C^{-1}g \rangle_{Q', Q} \geq \frac{\gamma}{C_c^2} \|g\|_{Q'}^2, \quad \forall g \in Q'. \tag{52}$$

Theorem 21. Assume that (51) holds true and that the bilinear forms a and c are both symmetric and positive. Suppose in addition that there exists a constant $\alpha_B > 0$ such that

$$a(u, u) + \frac{\gamma}{2C_c^2} \|Bu\|_{Q'}^2 \geq \alpha_B \|u\|_V^2, \quad \forall u \in V, \tag{53}$$

then Problem (37) is well-posed and

$$\|(u, p)\|_{V \times Q} \leq C \|(f, g)\|_{V' \times Q'},$$

with C a constant depending only on α_B, γ and C_b .

Proof. For $\eta, \mu > 0$, we consider the mapping

$$\begin{aligned} \mathbb{T} : V \times Q &\longrightarrow V \times Q \\ (u, p) &\longmapsto (u, -\eta p + \mu C^{-1}(Bu)). \end{aligned}$$

Then, using the definitions of C^{-1} and B , we compute

$$\begin{aligned} \mathcal{A}_c((u, p), \mathbb{T}(u, p)) &= a(u, u) + b(u, p) - \eta b(u, p) + \mu b(u, C^{-1}Bu) + \eta c(p, p) - \mu c(p, C^{-1}Bu) \\ &= a(u, u) + (1 - \eta)b(u, p) + \mu \langle Bu, C^{-1}Bu \rangle_{Q',Q} + \eta c(p, p) - \mu \langle Bu, p \rangle_{Q',Q} \\ &= a(u, u) + (1 - \eta - \mu)b(u, p) + \mu \langle Bu, C^{-1}Bu \rangle_{Q',Q} + \eta c(p, p). \end{aligned}$$

Let us choose $\eta, \mu > 0$ such that $\eta + \mu = 1$ to cancel the second term above. To fix ideas, let $\eta = \mu = 1/2$, so that

$$\mathbb{T}(u, p) = \left(u, -\frac{1}{2}p + \frac{1}{2}C^{-1}(Bu) \right) \tag{54}$$

and

$$\mathcal{A}_c((u, p), \mathbb{T}(u, p)) = a(u, u) + \frac{1}{2} \langle Bu, C^{-1}Bu \rangle_{Q',Q} + \frac{1}{2}c(p, p).$$

Owing to (52) and (51), we deduce that

$$\mathcal{A}_c((u, p), \mathbb{T}(u, p)) \geq a(u, u) + \frac{\gamma}{2C_c^2} \|Bu\|_{Q'}^2 + \frac{\gamma}{2} \|p\|_Q^2,$$

and the result follows. □

Remark 22. The \mathbb{T} -coercivity estimate reads

$$\mathcal{A}_c((u, p), \mathbb{T}(u, p)) \geq \alpha_B \|u\|_V^2 + \frac{\gamma}{2} \|p\|_Q^2, \tag{55}$$

so that it depends on γ , whereas it was independent of ε in the small perturbation case. Moreover, because of the term $C^{-1}(Bu)$ in (54), $\|\mathbb{T}\|$ behaves as γ^{-1} . Nevertheless, the final stability estimate is robust because the value of the constant γ is fixed.

Remark 23. Note that Theorem 21 does not require the inf-sup condition (18) to be true. However, if (18) holds, then (53) is automatically satisfied. As a matter of fact, for any $u \in V$, using the decomposition $u = u_0 + \bar{u}$ with $u_0 \in \text{Ker} B$ and $\bar{u} \in (\text{Ker} B)^\perp$, we have seen in the proof of Theorem 11 that, for all $0 < \theta < 1$, it holds

$$a(u, u) \geq (1 - \theta)a(u_0, u_0) + \left(C_a - \frac{C_a}{\theta} \right) \|\bar{u}\|_V^2 \quad \text{and} \quad \|Bu\|_{Q'}^2 = \|B\bar{u}\|_Q^2 \geq \beta^{-2} \|\bar{u}\|_V^2.$$

Hence,

$$a(u, u) + \frac{\gamma}{2C_c^2} \|Bu\|_{Q'}^2 \geq (1 - \theta)a(u_0, u_0) + \left(C_a - \frac{C_a}{\theta} + \frac{\gamma}{2C_c^2} \beta^{-2} \right) \|\bar{u}\|_V^2.$$

We then observe that

$$\left(C_a - \frac{C_a}{\theta} + \frac{\gamma}{2C_c^2} \beta^{-2} \right) > 0, \quad \forall \theta \in \left(\left(1 + \frac{\gamma}{2C_c^2 C_a} \beta^{-2} \right)^{-1}, 1 \right),$$

so (53) is obtained by choosing some $\theta = \theta(C_a, \beta, C_c, \gamma)$ in the above interval.

Remark 24. We will see in Section 6 that Theorem 21 is sufficient to handle the case of neutron diffusion. Nevertheless, note that assumption (53) is not optimal since it depends on the arbitrary choice $\eta = \mu = 1/2$ made in the proof. Looking through the proof, we see that the result of Theorem 21 still holds true as long as there exist $\tilde{\alpha}_B > 0$ and $0 < \tilde{\mu} < 1$ such that

$$a(u, u) + \tilde{\mu} \langle Bu, C^{-1}Bu \rangle_{Q',Q} \geq \tilde{\alpha}_B \|u\|_V^2, \quad \forall u \in V.$$

The final \mathbb{T} -coercivity estimate then reads

$$\mathcal{A}_c((u, p), \mathbb{T}(u, p)) \geq \tilde{\alpha}_B \|u\|_V^2 + (1 - \tilde{\mu})\gamma \|p\|_Q^2.$$

However, this estimate is possibly less sharp than (55) if $\tilde{\mu} > \frac{1}{2}$.

In addition to the Stokes problem, let us see next how other typical examples of mixed formulations fall within the T-coercivity framework.

4. Application to electromagnetism

Our goal is to solve the so-called quasi-static magnetic problem set in a homogeneous or an anisotropic medium, surrounded by a perfect conductor (see [1, Section 6.4]). The medium is characterized by its dielectric permittivity $\underline{\varepsilon}$ and its magnetic permeability $\underline{\mu}$.

Let Ω be the domain of \mathbb{R}^3 in which the problem is set. For simplicity, we assume that Ω is simply connected, with a connected boundary. Moreover, we assume that $\xi \in \{\underline{\varepsilon}, \underline{\mu}\}$ satisfy the following assumption:

$$\begin{cases} \xi \text{ is a real-valued, symmetric, measurable tensor field on } \Omega, \\ \exists \xi_-, \xi_+ > 0, \forall \mathbf{z} \in \mathbb{R}^3, \xi_- |\mathbf{z}|^2 \leq \xi \cdot \mathbf{z} \leq \xi_+ |\mathbf{z}|^2 \text{ a.e. in } \Omega. \end{cases} \tag{56}$$

Because one is dealing with symmetric tensors, if ξ fulfills (56), so does ξ^{-1} , with $(\xi^{-1})_+ = (\xi_-)^{-1}$ and $(\xi^{-1})_- = (\xi_+)^{-1}$.

Given $\mathbf{H}^* \in L^2(\Omega)$, such that $\underline{\mu} \mathbf{H}^* \in \mathbf{H}_0(\text{div}; \Omega) \cap \mathbf{H}(\text{div}0; \Omega)$ and $\rho \in H^{-1}(\Omega)$, the quasi-static magnetic problem amounts to finding $\mathbf{E} \in L^2(\Omega)$ such that

$$\begin{aligned} \underline{\mu}^{-1} \mathbf{curl} \mathbf{E} &= \mathbf{H}^*, & \text{in } \Omega, \\ \text{div}(\underline{\varepsilon} \mathbf{E}) &= \rho, & \text{in } \Omega, \\ \mathbf{E} \times \mathbf{n} &= 0, & \text{on } \partial\Omega. \end{aligned} \tag{57}$$

Under the assumptions on $\underline{\varepsilon}$ and $\underline{\mu}$, on the one hand we note that $\mathbf{E} \in \mathbf{H}_0(\mathbf{curl}; \Omega)$. On the other hand, it is known that the problem (57) is well-posed, see for instance [1, Theorem 6.1.4]. Below, we propose to recover well-posedness using the T-coercivity approach.

4.1. Proving well-posedness with T-coercivity

4.1.1. In a homogeneous medium

Let us first assume that $\underline{\varepsilon} = \underline{\mu} = \mathbb{I}_3$ in Ω . To build an all-in-one equivalent variational formulation, we follow e.g. [26]. In this case, the electromagnetic energy can be expressed in terms of the electric field as $(\mathbf{E}, \mathbf{E})_{L^2(\Omega)} + (\mathbf{curl} \mathbf{E}, \mathbf{curl} \mathbf{E})_{L^2(\Omega)}$. In other words, it is equal to $\|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl}; \Omega)}^2$, where $\|\cdot\|_{\mathbf{H}(\mathbf{curl}; \Omega)}$ denotes the “natural” norm in $\mathbf{H}(\mathbf{curl}; \Omega)$. We endow $H_0^1(\Omega)$ with $\|\nabla \cdot\|$ and the corresponding inner product $(\nabla \cdot, \nabla \cdot)_{L^2(\Omega)}$. Bearing in mind that $\mathbf{curl}(\nabla p) = 0$, it follows that

$$\|\nabla q\| = \|\nabla q\|_{\mathbf{H}(\mathbf{curl}; \Omega)}, \quad \forall q \in H_0^1(\Omega).$$

First, for $\mathbf{H}^* \in \mathbf{H}_0(\text{div}; \Omega) \cap \mathbf{H}(\text{div}0; \Omega)$ and $\rho \in H^{-1}(\Omega)$, one can prove that the equivalent weak formulation of Problem (57) reads: find $\mathbf{E} \in \mathbf{H}_0(\mathbf{curl}; \Omega)$ such that

$$\begin{aligned} (\mathbf{curl} \mathbf{E}, \mathbf{curl} \mathbf{v})_{L^2(\Omega)} &= (\mathbf{H}^*, \mathbf{curl} \mathbf{v})_{L^2(\Omega)}, & \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \\ (\mathbf{E}, \nabla q)_{L^2(\Omega)} &= -\langle \rho, q \rangle_{H^{-1}(\Omega), H_0^1(\Omega)}, & \forall q \in H_0^1(\Omega). \end{aligned}$$

Second, in order to fit (57) into the abstract framework (15), we introduce an artificial pressure unknown \tilde{p} by adding a term $(\mathbf{v}, \nabla \tilde{p})_{L^2(\Omega)}$ in the first equation. The previous formulation becomes: find $(\mathbf{E}, \tilde{p}) \in \mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega)$ such that

$$\begin{aligned} (\mathbf{curl} \mathbf{E}, \mathbf{curl} \mathbf{v})_{L^2(\Omega)} + (\mathbf{v}, \nabla \tilde{p})_{L^2(\Omega)} &= (\mathbf{H}^*, \mathbf{curl} \mathbf{v})_{L^2(\Omega)}, & \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \\ (\mathbf{E}, \nabla q)_{L^2(\Omega)} &= -\langle \rho, q \rangle_{H^{-1}(\Omega), H_0^1(\Omega)}, & \forall q \in H_0^1(\Omega). \end{aligned} \tag{58}$$

Indeed, one can easily check that (\mathbf{E}, \tilde{p}) is solution of (58) if and only if $\tilde{p} = 0$ and \mathbf{E} is solution of (57). So, defining the bilinear forms

$$\begin{aligned} a(\mathbf{u}, \mathbf{v}) &= (\mathbf{curl} \mathbf{u}, \mathbf{curl} \mathbf{v})_{L^2(\Omega)}, \quad \forall \mathbf{u} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \\ b(\mathbf{v}, q) &= (\mathbf{v}, \nabla q)_{L^2(\Omega)}, \quad \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \forall q \in H_0^1(\Omega), \end{aligned}$$

the *all-in-one* bilinear and linear forms of Maxwell problem are respectively given by

$$\mathcal{A}((\mathbf{E}, \tilde{p}), (\mathbf{v}, q)) = a(\mathbf{E}, \mathbf{v}) + b(\mathbf{v}, \tilde{p}) + b(\mathbf{E}, q), \quad (59)$$

$$\ell((\mathbf{v}, q)) = (\mathbf{H}^*, \mathbf{curl} \mathbf{v})_{L^2(\Omega)} - \langle \rho, q \rangle_{H^{-1}(\Omega), H_0^1(\Omega)}. \quad (60)$$

The continuity constants are such that $C_a = 1$, $C_b = 1$, and $C_\ell \leq (\|\mathbf{H}^*\|^2 + \|\rho\|_{H^{-1}(\Omega)}^2)^{1/2}$.

Let us give an explicit expression of the abstract operators

$$\mathbf{B} \in \mathcal{L}(\mathbf{H}_0(\mathbf{curl}; \Omega), H_0^1(\Omega)), \quad \mathbf{L}_B \in \mathcal{L}(H_0^1(\Omega), (\text{KerB})^\perp)$$

corresponding to this problem. According to (19), for $\mathbf{u} \in \mathbf{H}_0(\mathbf{curl}; \Omega)$,

$$\mathbf{B}\mathbf{u} = 0 \iff (\mathbf{u}, \nabla q)_{L^2(\Omega)} = 0, \quad \forall q \in H_0^1(\Omega) \iff \text{div} \mathbf{u} = 0.$$

Hence,

$$\text{KerB} = \mathbf{K}_N(\Omega), \quad \text{where } \mathbf{K}_N(\Omega) = \mathbf{H}_0(\mathbf{curl}; \Omega) \cap \mathbf{H}(\text{div} 0; \Omega). \quad (61)$$

In addition, one easily checks that

$$(\text{KerB})^\perp = \{\mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \exists q \in H_0^1(\Omega), \mathbf{v} = \nabla q\}. \quad (62)$$

With those results, we can characterize \mathbf{L}_B . On the one hand, by definition of b , we observe that

$$b(\mathbf{L}_B p, q) = (\mathbf{L}_B p, \nabla q)_{L^2(\Omega)}, \quad \forall p, q \in H_0^1(\Omega). \quad (63)$$

On the other hand, according to (20), one has

$$b(\mathbf{L}_B p, q) = (\nabla p, \nabla q)_{L^2(\Omega)}, \quad \forall p, q \in H_0^1(\Omega). \quad (64)$$

Putting (62), (63) and (64) together, we deduce that

$$\mathbf{L}_B p = \nabla p.$$

Moreover, for all $p \in H_0^1(\Omega)$, one has

$$\|\mathbf{L}_B p\|_{\mathbf{H}(\mathbf{curl}; \Omega)} = \|\nabla p\|_{\mathbf{H}(\mathbf{curl}; \Omega)} = \|\nabla p\|,$$

hence \mathbf{L}_B is an isometry, so \mathbf{L}_B satisfies (22) with $\beta = 1$. The inf-sup condition (18) holds.

Going back to KerB (cf. (61)), we recall Weber inequality [47]: there exists $C_K > 1$ such that

$$\|\mathbf{k}\|_{\mathbf{H}(\mathbf{curl}; \Omega)} \leq C_K \|\mathbf{curl} \mathbf{k}\|, \quad \forall \mathbf{k} \in \mathbf{K}_N(\Omega).$$

The fact that C_K cannot be taken smaller than 1 stems from the definition of the “natural” norms involved. Hence, Weber inequality says that the form a is coercive on KerB , so that all the conditions of Theorem 11 are fulfilled, with $\alpha_0 = (C_K)^{-2} < 1$. Precisely, Theorem 11 states that the bilinear form \mathcal{A} is T-coercive for the mapping

$$\begin{aligned} \mathbf{T} : \mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega) &\longrightarrow \mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega) \\ (\mathbf{E}, \tilde{p}) &\longmapsto \left(\mathbf{E} + \nabla \tilde{p}, -\tilde{p} + \frac{3}{4} \mathbf{B}\mathbf{E} \right), \end{aligned} \quad (65)$$

where, by definition of the operator \mathbf{B} (cf. (19)), $\mathbf{B}\mathbf{E} \in H_0^1(\Omega)$ satisfies

$$(\nabla(\mathbf{B}\mathbf{E}), \nabla q)_{L^2(\Omega)} = b(\mathbf{E}, q) = (\mathbf{E}, \nabla q)_{L^2(\Omega)}, \quad \forall q \in H_0^1(\Omega). \quad (66)$$

Furthermore, following (31), it holds that

$$\mathcal{A}((\mathbf{E}, \tilde{p}), \mathbf{T}(\mathbf{E}, \tilde{p})) \geq \frac{(C_K)^{-2}}{4} \|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl}; \Omega)}^2 + \frac{1}{2} \|\nabla \tilde{p}\|_{L^2(\Omega)}^2 \geq \underline{\alpha} \left(\|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl}; \Omega)}^2 + \|\nabla \tilde{p}\|_{L^2(\Omega)}^2 \right),$$

with $\alpha = \frac{(C_K)^{-2}}{4}$.

To get the stability constant, we need to compute $\|T\|$, that is, bound $\|T(\mathbf{E}, \tilde{p})\|_{\mathbf{H}_0(\mathbf{curl};\Omega) \times H_0^1(\Omega)}$ for $(\mathbf{E}, \tilde{p}) \in \mathbf{H}_0(\mathbf{curl};\Omega) \times H_0^1(\Omega)$. We find that

$$\begin{aligned} \|T(\mathbf{E}, \tilde{p})\|_{\mathbf{H}_0(\mathbf{curl};\Omega) \times H_0^1(\Omega)}^2 &= \|\mathbf{E} + \nabla \tilde{p}\|_{\mathbf{H}(\mathbf{curl};\Omega)}^2 + \left\| -\nabla \tilde{p} + \frac{3}{4} \nabla(\mathbf{B}\mathbf{E}) \right\|_{L^2(\Omega)}^2 \\ &\leq 2 \|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl};\Omega)}^2 + 2 \|\nabla \tilde{p}\|_{\mathbf{H}(\mathbf{curl};\Omega)}^2 + 2 \|\nabla \tilde{p}\|_{L^2(\Omega)}^2 + 2 \cdot \left(\frac{3}{4}\right)^2 \|\nabla(\mathbf{B}\mathbf{E})\|_{L^2(\Omega)}^2 \\ &\leq 2 \|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl};\Omega)}^2 + 4 \|\nabla \tilde{p}\|_{L^2(\Omega)}^2 + 2 \cdot \left(\frac{3}{4}\right)^2 \|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl};\Omega)}^2 \\ &\leq 4 \left(\|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl};\Omega)}^2 + \|\nabla \tilde{p}\|_{L^2(\Omega)}^2 \right), \end{aligned}$$

where we used that $\|\nabla(\mathbf{B}\mathbf{E})\|_{L^2(\Omega)} \leq \|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl};\Omega)}$ thanks to (66). Therefore, $\|T\| \leq 2$.

Applying (4), we conclude that

$$\|\mathbf{E}\|_{\mathbf{H}(\mathbf{curl};\Omega)} \leq 8C_K^2 \left(\|\mathbf{H}^*\|^2 + \|\rho\|_{H^{-1}(\Omega)}^2 \right)^{1/2}. \tag{67}$$

4.1.2. In an anisotropic medium

In an anisotropic medium, let us follow for instance [25] to build an all-in-one equivalent variational formulation. In this case, the electromagnetic energy can be expressed as $(\underline{\varepsilon}\mathbf{E}, \mathbf{E})_{L^2(\Omega)} + (\underline{\mu}^{-1}\mathbf{curl}\mathbf{E}, \mathbf{curl}\mathbf{E})_{L^2(\Omega)}$. Under the assumption (56) on $\underline{\varepsilon}$ and $\underline{\mu}$, we note that we can endow $\mathbf{H}_0(\mathbf{curl};\Omega)$ with the inner product

$$(\cdot, \cdot)_{\underline{\varepsilon}, \underline{\mu}^{-1}\mathbf{curl}} : (\mathbf{u}, \mathbf{v}) \mapsto (\underline{\varepsilon}\mathbf{u}, \mathbf{v})_{L^2(\Omega)} + (\underline{\mu}^{-1}\mathbf{curl}\mathbf{u}, \mathbf{curl}\mathbf{v})_{L^2(\Omega)}.$$

The associated scaled norm

$$\|\mathbf{u}\|_{\underline{\varepsilon}, \underline{\mu}^{-1}\mathbf{curl}} = \left((\underline{\varepsilon}\mathbf{u}, \mathbf{u})_{L^2(\Omega)} + (\underline{\mu}^{-1}\mathbf{curl}\mathbf{u}, \mathbf{curl}\mathbf{u})_{L^2(\Omega)} \right)^{1/2}$$

is equivalent to the “natural” norm. Then, we endow $H_0^1(\Omega)$ with the inner product $(\cdot, \cdot)_{1, \underline{\varepsilon}} : (p, q) \mapsto (\underline{\varepsilon}\nabla p, \nabla q)_{L^2(\Omega)}$, and the associated scaled norm

$$\|q\|_{1, \underline{\varepsilon}} = \left((\underline{\varepsilon}\nabla q, \nabla q)_{L^2(\Omega)} \right)^{1/2}$$

is equivalent to $\|\cdot\|_{H^1(\Omega)}$ according to Poincaré inequality. With this choice of norms, for $q \in H_0^1(\Omega)$, one has $\|q\|_{1, \underline{\varepsilon}} = \|\nabla q\|_{\underline{\varepsilon}, \underline{\mu}^{-1}\mathbf{curl}}$. Also, $\mathbb{1}_{H_0^1(\Omega) \rightarrow H^{-1}(\Omega)}$ is the isomorphism defined by

$$\left\langle \mathbb{1}_{H_0^1(\Omega) \rightarrow H^{-1}(\Omega)} p, q \right\rangle_{H^{-1}(\Omega), H_0^1(\Omega)} = (p, q)_{1, \underline{\varepsilon}} = (\underline{\varepsilon}\nabla p, \nabla q)_{L^2(\Omega)}, \quad \forall p, q \in H_0^1(\Omega),$$

while the norm in $H^{-1}(\Omega)$ is

$$\|g\|_{-1, \underline{\varepsilon}^{-1}} = \sup_{q \in H_0^1(\Omega) \setminus \{0\}} \frac{\langle g, q \rangle_{H^{-1}(\Omega), H_0^1(\Omega)}}{\|q\|_{1, \underline{\varepsilon}}}, \quad \forall g \in H^{-1}(\Omega).$$

Finally, for $\xi \in \{\underline{\varepsilon}, \underline{\varepsilon}^{-1}, \underline{\mu}, \underline{\mu}^{-1}\}$, we use the inner product $(\cdot, \cdot)_\xi : (\mathbf{u}, \mathbf{v}) \mapsto (\xi\mathbf{u}, \mathbf{v})_{L^2(\Omega)}$, and the associated scaled norm $\|\cdot\|_\xi$ in $L^2(\Omega)$. As we shall see below, these scaled norms and inner products, which are introduced to account for the anisotropic medium, lead to computations that are very similar to those that have been carried out for a homogeneous medium.

As before, in order to fit (57) into the abstract framework (15), we introduce a vanishing artificial pressure \tilde{p} . The resulting formulation is: find $(\mathbf{E}, \tilde{p}) \in \mathbf{H}_0(\mathbf{curl};\Omega) \times H_0^1(\Omega)$ such that

$$\begin{aligned} (\underline{\mu}^{-1}\mathbf{curl}\mathbf{E}, \mathbf{curl}\mathbf{v})_{L^2(\Omega)} + (\underline{\varepsilon}\mathbf{v}, \nabla \tilde{p})_{L^2(\Omega)} &= (\mathbf{H}^*, \mathbf{curl}\mathbf{v})_{L^2(\Omega)}, \quad \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl};\Omega), \\ (\underline{\varepsilon}\mathbf{E}, \nabla q)_{L^2(\Omega)} &= -\langle \rho, q \rangle_{H^{-1}(\Omega), H_0^1(\Omega)}, \quad \forall q \in H_0^1(\Omega). \end{aligned} \tag{68}$$

So, defining the bilinear forms

$$\begin{aligned} a_{\underline{\mu}^{-1}}(\mathbf{u}, \mathbf{v}) &= \left(\underline{\mu}^{-1} \mathbf{curl} \mathbf{u}, \mathbf{curl} \mathbf{v} \right)_{L^2(\Omega)}, \quad \forall \mathbf{u} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \\ b_{\underline{\varepsilon}}(\mathbf{v}, q) &= (\underline{\varepsilon} \mathbf{v}, \nabla q)_{L^2(\Omega)}, \quad \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \forall q \in H_0^1(\Omega), \end{aligned}$$

the *all-in-one* bilinear form of Maxwell problem is now given by

$$\mathcal{A}_{\underline{\varepsilon}, \underline{\mu}}((\mathbf{E}, \tilde{\mathbf{p}}), (\mathbf{v}, q)) = a_{\underline{\mu}^{-1}}(\mathbf{E}, \mathbf{v}) + b_{\underline{\varepsilon}}(\mathbf{v}, \tilde{\mathbf{p}}) + b_{\underline{\varepsilon}}(\mathbf{E}, q), \tag{69}$$

while the linear form remains defined by (60). Thanks to the introduction of scaled norms, we find that the bilinear form $a_{\underline{\mu}^{-1}}$ is continuous on $\mathbf{H}_0(\mathbf{curl}; \Omega) \times \mathbf{H}_0(\mathbf{curl}; \Omega)$ with a continuity constant $C_a = 1$, while the bilinear form $b_{\underline{\varepsilon}}$ is continuous on $\mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega)$ with a continuity constant $C_b = 1$. With respect to the scaled norms, we have

$$\left| (\mathbf{H}^*, \mathbf{curl} \mathbf{v})_{L^2(\Omega)} - \langle \rho, q \rangle_{H^{-1}(\Omega), H_0^1(\Omega)} \right| \leq \| \mathbf{H}^* \|_{\underline{\mu}} \| \mathbf{curl} \mathbf{v} \|_{\underline{\mu}^{-1}} + \| \rho \|_{-1, \underline{\varepsilon}^{-1}} \| q \|_{1, \underline{\varepsilon}},$$

so that $C_\ell \leq (\| \mathbf{H}^* \|_{\underline{\mu}}^2 + \| \rho \|_{-1, \underline{\varepsilon}^{-1}}^2)^{1/2}$. Let us give an explicit expression of the abstract operators

$$B_{\underline{\varepsilon}} \in \mathcal{L}(\mathbf{H}_0(\mathbf{curl}; \Omega), H_0^1(\Omega)), \quad L_{B_{\underline{\varepsilon}}} \in \mathcal{L}(H_0^1(\Omega), (\text{Ker} B_{\underline{\varepsilon}})^\perp).$$

Given $\mathbf{u} \in \mathbf{H}_0(\mathbf{curl}; \Omega)$, we observe that, by definition of operator $B_{\underline{\varepsilon}}$ (cf. (19))

$$B_{\underline{\varepsilon}} \mathbf{u} = 0 \iff (\underline{\varepsilon} \mathbf{u}, \nabla q)_{L^2(\Omega)} = 0, \quad \forall q \in H_0^1(\Omega) \iff \text{div}(\underline{\varepsilon} \mathbf{u}) = 0.$$

Hence,

$$\text{Ker} B_{\underline{\varepsilon}} = \mathbf{K}_N(\Omega; \underline{\varepsilon}), \quad \text{where } \mathbf{K}_N(\Omega; \underline{\varepsilon}) = \{ \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \text{div}(\underline{\varepsilon} \mathbf{v}) = 0 \}. \tag{70}$$

In addition (see e.g. [1, (6.16)])

$$(\text{Ker} B_{\underline{\varepsilon}})^\perp = \{ \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \exists q \in H_0^1(\Omega), \mathbf{v} = \nabla q \}, \tag{71}$$

where orthogonality is understood with respect to the inner product $(\cdot, \cdot)_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}$.

With those results, we can characterize $L_{B_{\underline{\varepsilon}}}$. By definition of $b_{\underline{\varepsilon}}$, we observe that

$$b_{\underline{\varepsilon}}(L_{B_{\underline{\varepsilon}}} p, q) = (\underline{\varepsilon} (L_{B_{\underline{\varepsilon}}} p), \nabla q)_{L^2(\Omega)}, \quad \forall p, q \in H_0^1(\Omega). \tag{72}$$

While, according to (20), one has

$$b_{\underline{\varepsilon}}(L_{B_{\underline{\varepsilon}}} p, q) = (p, q)_{1, \underline{\varepsilon}} = (\underline{\varepsilon} \nabla p, \nabla q)_{L^2(\Omega)}, \quad \forall p, q \in H_0^1(\Omega). \tag{73}$$

Putting (71), (72) and (73) together, we deduce that $L_{B_{\underline{\varepsilon}}} p = \nabla p$. So, for all $p \in H_0^1(\Omega)$, it follows that $\| L_{B_{\underline{\varepsilon}}} p \|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} = \| p \|_{1, \underline{\varepsilon}}$. In other words, $L_{B_{\underline{\varepsilon}}}$ is an isometry with respect to the scaled norms: $L_{B_{\underline{\varepsilon}}}$ satisfies (22) with $\beta = 1$, and the inf-sup condition (18) holds.

Going back to $\text{Ker} B_{\underline{\varepsilon}}$ (cf. (70)), we recall the generalized Weber inequality [47] (or [1, Theorem 6.1.4]): there exists $C_K > 1$ such that

$$\| \mathbf{k} \|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \leq C_K \| \mathbf{curl} \mathbf{k} \|_{\underline{\mu}^{-1}}, \quad \forall \mathbf{k} \in \mathbf{K}_N(\Omega; \underline{\varepsilon}).$$

While the bound $C_K > 1$ remains as a consequence of the definition of the scaled norms, the value of the constant C_K now possibly depends on $\underline{\varepsilon}$ or $\underline{\mu}$.

The generalized Weber inequality implies that the form $a_{\underline{\mu}^{-1}}$ is coercive on $\text{Ker} B_{\underline{\varepsilon}}$: all the conditions of Theorem 11 are fulfilled, with $\alpha_0 = (C_K)^{-2} < 1$. Interestingly, Theorem 11 states that the bilinear form $\mathcal{A}_{\underline{\varepsilon}, \underline{\mu}}$ is T-coercive for the mapping T that is again given by (65), but replacing B by the $\underline{\varepsilon}$ -dependent operator $B_{\underline{\varepsilon}}$. Based on this observation, the final computations are very close to those of Section 4.1.1, replacing the “natural” norms and inner products by their scaled counterparts.

First, using (19), we find that $B_{\underline{\varepsilon}} \mathbf{E} \in H_0^1(\Omega)$ satisfies

$$(\underline{\varepsilon} \nabla (B_{\underline{\varepsilon}} \mathbf{E}), \nabla q)_{L^2(\Omega)} = (\underline{\varepsilon} \mathbf{E}, \nabla q)_{L^2(\Omega)}, \quad \forall q \in H_0^1(\Omega). \tag{74}$$

Second, following (31) and introducing $\underline{\alpha} = \frac{(C_K)^{-2}}{4}$ (which depends on $\underline{\varepsilon}$ or $\underline{\mu}$), it holds that

$$\mathcal{A}_{\underline{\varepsilon}, \underline{\mu}}((\mathbf{E}, \tilde{\mathbf{p}}), \mathbf{T}(\mathbf{E}, \tilde{\mathbf{p}})) \geq \underline{\alpha} \left(\|\mathbf{E}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 + \|\tilde{\mathbf{p}}\|_{1, \underline{\varepsilon}}^2 \right).$$

Finally, thanks to (74), which yields $\|\mathbf{B}_{\underline{\varepsilon}} \mathbf{E}\|_{1, \underline{\varepsilon}} \leq \|\mathbf{E}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}$, we now find that

$$\begin{aligned} \|\mathbf{T}(\mathbf{E}, \tilde{\mathbf{p}})\|_{\mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega)}^2 &= \|\mathbf{E} + \nabla \tilde{\mathbf{p}}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 + \left\| -\tilde{\mathbf{p}} + \frac{3}{4} \mathbf{B}_{\underline{\varepsilon}} \mathbf{E} \right\|_{1, \underline{\varepsilon}}^2 \\ &\leq 4 \left(\|\mathbf{E}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 + \|\tilde{\mathbf{p}}\|_{1, \underline{\varepsilon}}^2 \right). \end{aligned}$$

Using the scaled norms, we have again that $\|\mathbf{T}\| \leq 2$, and we conclude with (4) that

$$\|\mathbf{E}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \leq 8C_K^2 \left(\|\mathbf{H}^*\|_{\underline{\mu}}^2 + \|\rho\|_{-1, \underline{\varepsilon}^{-1}}^2 \right)^{1/2}. \tag{75}$$

4.2. Optimized bounds in an anisotropic medium

To achieve T-coercivity, the abstract theory does not take into account the so-called double orthogonality property (or Helmholtz decomposition), which states that for all $\mathbf{k} \in \mathbf{K}_N(\Omega; \underline{\varepsilon})$ and all $q \in H_0^1(\Omega)$, one has $(\underline{\varepsilon} \mathbf{k}, \nabla q)_{L^2(\Omega)} = (\underline{\mu}^{-1} \mathbf{curl} \mathbf{k}, \mathbf{curl}(\nabla q))_{L^2(\Omega)} = 0$, so that

$$\|\mathbf{k} + \nabla q\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 = \|\mathbf{k}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 + \|q\|_{1, \underline{\varepsilon}}^2.$$

Indeed, given $\mathbf{E} \in \mathbf{H}_0(\mathbf{curl}; \Omega)$, we note that, with the help of $\phi_E := \mathbf{B}_{\underline{\varepsilon}} \mathbf{E} \in H_0^1(\Omega)$ solving (74), one has the (orthogonal) Helmholtz decomposition

$$\mathbf{E} = \mathbf{k}_E + \nabla \phi_E,$$

with $\mathbf{k}_E \in \mathbf{K}_N(\Omega; \underline{\varepsilon})$.

We sketch below how one can improve the estimates, see [26] for further details. Let us choose

$$\begin{aligned} \mathbf{T}_{opt} : \mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega) &\longrightarrow \mathbf{H}_0(\mathbf{curl}; \Omega) \times H_0^1(\Omega) \\ (\mathbf{E}, \tilde{\mathbf{p}}) &\longmapsto (\mathbf{k}_E + \nabla \tilde{\mathbf{p}}, \phi_E). \end{aligned}$$

Thanks to the double orthogonality property, one finds easily that \mathbf{T}_{opt} is an isometry and that

$$\begin{aligned} \mathcal{A}_{\underline{\varepsilon}, \underline{\mu}}((\mathbf{E}, \tilde{\mathbf{p}}), \mathbf{T}_{opt}(\mathbf{E}, \tilde{\mathbf{p}})) &= \|\mathbf{curl} \mathbf{k}_E\|_{\underline{\mu}^{-1}}^2 + \|\tilde{\mathbf{p}}\|_{1, \underline{\varepsilon}}^2 + \|\phi_E\|_{1, \underline{\varepsilon}}^2 \\ &\geq (C_K)^{-2} \left(\|\mathbf{E}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 + \|\tilde{\mathbf{p}}\|_{1, \underline{\varepsilon}}^2 \right), \end{aligned}$$

where C_K is the constant that appears in the generalized Weber inequality. Applying (4), we have the optimized stability estimate

$$\|\mathbf{E}\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \leq C_K^2 \left(\|\mathbf{H}^*\|_{\underline{\mu}}^2 + \|\rho\|_{-1, \underline{\varepsilon}^{-1}}^2 \right)^{1/2}. \tag{76}$$

We conclude that, for all possible choices of coefficients $\underline{\varepsilon}$ and $\underline{\mu}$, there is only a factor 8 difference between the stability constant obtained via the abstract T-coercivity approach, see (75), and the optimized stability constant which relies explicitly on the double orthogonality property, see (76).

Remark 25. One can obtain similar results in more general geometries, such as a non-simply-connected domain, or a non-connected boundary, see [26].

5. Application to nearly-incompressible elasticity

In this section, we apply the T-coercivity framework to the equations of elasticity, assuming homogeneous Dirichlet boundary conditions. Let $\Omega \subset \mathbb{R}^d$ be a domain, where $d \in \{2, 3\}$. For a prescribed body force $\mathbf{f} \in \mathbf{H}^{-1}(\Omega)$, we look for the displacement $\mathbf{u} \in \mathbf{H}^1(\Omega)$ such that

$$\begin{aligned} -\operatorname{div}(\boldsymbol{\sigma}(\mathbf{u})) &= \mathbf{f}, & \text{in } \Omega, \\ \mathbf{u} &= 0, & \text{on } \partial\Omega, \end{aligned} \tag{77}$$

where $\boldsymbol{\sigma}(\mathbf{u})$ denotes the stress tensor. We assume that it is given by Hooke's law

$$\boldsymbol{\sigma}(\mathbf{u}) = 2\mu \boldsymbol{\varepsilon}(\mathbf{u}) + \lambda(\operatorname{div} \mathbf{u})I,$$

where $\lambda, \mu > 0$ are the Lamé coefficients of the material and $\boldsymbol{\varepsilon}(\mathbf{u}) = \frac{1}{2}(\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$ is the linearized strain tensor. Thanks to Korn inequality [29], the space $\mathbf{H}_0^1(\Omega)$ is here endowed with the inner product

$$(\mathbf{u}, \mathbf{v}) \longmapsto \int_{\Omega} \boldsymbol{\varepsilon}(\mathbf{u}) : \boldsymbol{\varepsilon}(\mathbf{v}) \, dx,$$

whose associated norm $\mathbf{u} \mapsto \|\boldsymbol{\varepsilon}(\mathbf{u})\|$ is equivalent to the $\mathbf{H}^1(\Omega)$ -norm in $\mathbf{H}_0^1(\Omega)$. Introducing the new unknown $p = \lambda \operatorname{div} \mathbf{u}$, the elasticity system (77) can be written in mixed form as follows: find $\mathbf{u} \in \mathbf{H}_0^1(\Omega)$ and $p \in L_0^2(\Omega)$ such that

$$\begin{aligned} -2\mu \operatorname{div}(\boldsymbol{\varepsilon}(\mathbf{u})) - \nabla p &= \mathbf{f}, & \text{in } \Omega, \\ \operatorname{div} \mathbf{u} - \frac{1}{\lambda} p &= 0, & \text{in } \Omega. \end{aligned}$$

Or equivalently, in variational form: find $\mathbf{u} \in \mathbf{H}_0^1(\Omega)$ and $p \in L_0^2(\Omega)$ such that

$$\begin{aligned} a(\mathbf{u}, \mathbf{v}) + b(\mathbf{v}, p) &= \langle \mathbf{f}, \mathbf{v} \rangle, & \forall \mathbf{v} \in \mathbf{H}_0^1(\Omega), \\ b(\mathbf{u}, q) - \frac{1}{\lambda} c_0(p, q) &= 0, & \forall q \in L_0^2(\Omega), \end{aligned} \tag{78}$$

with

$$a(\mathbf{u}, \mathbf{v}) = 2\mu \int_{\Omega} \boldsymbol{\varepsilon}(\mathbf{u}) : \boldsymbol{\varepsilon}(\mathbf{v}) \, dx, \quad b(\mathbf{v}, q) = \int_{\Omega} q \operatorname{div} \mathbf{v} \, dx \quad \text{and} \quad c_0(p, q) = \int_{\Omega} p q \, dx.$$

For nearly-incompressible materials, the first Lamé coefficient λ goes to infinity, so that λ^{-1} goes to zero. Therefore, (78) can be seen as a small perturbation of Stokes system.

Since the bilinear form a is coercive on the whole space $\mathbf{H}_0^1(\Omega)$, we can directly apply Theorem 13 in the special case of Remark 14. The bilinear form a is continuous and coercive, with $C_a = \alpha = 2\mu$. In addition, the bilinear form b is continuous and satisfies the inf-sup condition (18) with $\beta = C_{\operatorname{div}}$ since b is the same form – except to the sign – as for Stokes problem. Then, Theorem 13 furnishes that the *all-in-one* bilinear form \mathcal{A}_c defined by

$$\mathcal{A}_c((\mathbf{u}, p), (\mathbf{v}, q)) = 2\mu \int_{\Omega} \boldsymbol{\varepsilon}(\mathbf{u}) : \boldsymbol{\varepsilon}(\mathbf{v}) \, dx + \int_{\Omega} p \operatorname{div} \mathbf{v} \, dx + \int_{\Omega} q \operatorname{div} \mathbf{u} \, dx - \frac{1}{\lambda} \int_{\Omega} p q \, dx \tag{79}$$

is T-coercive for the mapping

$$\begin{aligned} \mathbb{T} : \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega) &\longrightarrow \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega) \\ (\mathbf{u}, p) &\longmapsto (2\mu C_{\operatorname{div}}^2 \mathbf{u} + \mathbf{v}_{-p}, -2\mu C_{\operatorname{div}}^2 p), \end{aligned} \tag{80}$$

and (38) implies that

$$\mathcal{A}_c((\mathbf{u}, p), \mathbb{T}(\mathbf{u}, p)) \geq 2\mu^2 C_{\operatorname{div}}^2 \|\boldsymbol{\varepsilon}(\mathbf{u})\|^2 + \left(\frac{1}{2} + \frac{2\mu}{\lambda} C_{\operatorname{div}}^2 \right) \|p\|^2.$$

Note that this estimate is robust in the incompressible limit, namely for large values of λ .

Finally, replacing ν by 2μ in (11) and using (4), we get that the unique solution of (78) satisfies

$$\|(\mathbf{u}, p)\|_{\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)} \leq \frac{2 \max\left(2\sqrt{2}\mu C_{\text{div}}^2, C_{\text{div}}(2 + 4\mu^2 C_{\text{div}}^2)^{1/2}\right)}{\min(4\mu^2 C_{\text{div}}^2, 1 + 4\mu\lambda^{-1} C_{\text{div}}^2)} \|\mathbf{f}\|_{(\mathbf{H}_0^1(\Omega))'}$$

where $\|\cdot\|_{(\mathbf{H}_0^1(\Omega))'}$ denotes the dual norm of $\mathbf{H}_0^1(\Omega)$ endowed with $\|\varepsilon(\cdot)\|$.

6. Application to neutron diffusion

Let $\Omega \subset \mathbb{R}^d$ be a domain, where $d \in \{2, 3\}$. We consider the neutron diffusion equation with zero flux boundary condition: given a prescribed fission source $S_f \in L^2(\Omega)$, find $u \in H^1(\Omega)$ such that

$$\begin{aligned} -\operatorname{div}(D\nabla u) + \sigma u &= S_f, & \text{in } \Omega, \\ u &= 0, & \text{on } \partial\Omega, \end{aligned} \tag{81}$$

where u , D , and σ denote respectively the neutron flux, the diffusion coefficient and the macroscopic absorption cross section. It is assumed that the diffusion coefficient D fulfills (56), and that the macroscopic absorption cross section is such that

$$\begin{cases} \sigma \text{ is a real-valued measurable scalar field on } \Omega, \\ \exists \sigma_-, \sigma_+ > 0, \sigma_- \leq \sigma \leq \sigma_+ \text{ a.e. in } \Omega. \end{cases} \tag{82}$$

Because $S_f \in L^2(\Omega)$, one has $D\nabla u \in \mathbf{H}(\operatorname{div}; \Omega)$. This problem can be recast equivalently in mixed form, introducing the auxiliary unknown $\mathbf{p} = -D\nabla u$, called the neutron current. It reads: find $(u, \mathbf{p}) \in H_0^1(\Omega) \times \mathbf{H}(\operatorname{div}; \Omega)$ such that

$$\begin{aligned} \operatorname{div} \mathbf{p} + \sigma u &= S_f, & \text{in } \Omega, \\ D^{-1} \mathbf{p} + \nabla u &= 0, & \text{in } \Omega. \end{aligned} \tag{83}$$

It can be shown that an equivalent weak form is: find $(u, \mathbf{p}) \in L^2(\Omega) \times \mathbf{H}(\operatorname{div}; \Omega)$ such that

$$\int_{\Omega} (v \operatorname{div} \mathbf{p} + \sigma uv - D^{-1} \mathbf{p} \cdot \mathbf{q} + u \operatorname{div} \mathbf{q}) \, dx = \int_{\Omega} S_f v \, dx \quad \forall (v, \mathbf{q}) \in L^2(\Omega) \times \mathbf{H}(\operatorname{div}; \Omega). \tag{84}$$

Remark 26. Among other things, one can recover that the solution $u \in L^2(\Omega)$ from the weak form (84) is such that $u \in H^1(\Omega)$, and that $u = 0$ on $\partial\Omega$.

6.1. Proving well-posedness with T-coercivity

Defining the bilinear forms

$$\begin{aligned} a_{D^{-1}}(\mathbf{p}, \mathbf{q}) &= (D^{-1} \mathbf{p}, \mathbf{q})_{L^2(\Omega)}, & \forall \mathbf{p} \in \mathbf{H}(\operatorname{div}; \Omega), \forall \mathbf{q} \in \mathbf{H}(\operatorname{div}; \Omega), \\ b(\mathbf{q}, v) &= -(\operatorname{div} \mathbf{q}, v)_{L^2(\Omega)}, & \forall \mathbf{q} \in \mathbf{H}(\operatorname{div}; \Omega), \forall v \in L^2(\Omega), \\ c_{\sigma}(u, v) &= (\sigma u, v)_{L^2(\Omega)}, & \forall u \in L^2(\Omega), \forall v \in L^2(\Omega), \end{aligned}$$

the *all-in-one* bilinear form of the diffusion problem is given by

$$\mathcal{A}_c((\mathbf{p}, u), (\mathbf{q}, v)) = a_{D^{-1}}(\mathbf{p}, \mathbf{q}) + b(\mathbf{q}, u) + c_{\sigma}(u, v). \tag{85}$$

Here, we are in the case of a “fixed” augmentation, as treated in Section 3.6.

Let us check below that all the conditions of Theorem 21 are fulfilled. First, c_{σ} is coercive on $L^2(\Omega)$ with $\gamma = \sigma_-$. Then, $a_{D^{-1}}$ fulfills (13) with $C_a = (D_-)^{-1}$, whereas b fulfills (14) with $C_b = 1$.

Finally, we look for the condition (53). It is straightforward to check that, for all $\mathbf{p} \in \mathbf{H}(\text{div}; \Omega)$, $B\mathbf{p} = \mathbb{B}\mathbf{p} = -\text{div } \mathbf{p}$. Hence

$$\begin{aligned} a_{D^{-1}}(\mathbf{p}, \mathbf{p}) + \frac{\gamma}{2C_c^2} \|B\mathbf{p}\|^2 &= (D^{-1}\mathbf{p}, \mathbf{p}) + \frac{\sigma_-}{2\sigma_+^2} \|\text{div } \mathbf{p}\|^2 \\ &\geq \min\left((D_+)^{-1}, \frac{\sigma_-}{2\sigma_+^2}\right) \|\mathbf{p}\|_{\mathbf{H}(\text{div}; \Omega)}^2. \end{aligned}$$

Then, Theorem 21 establishes that the bilinear form \mathcal{A}_c is T-coercive for the mapping (54)

$$\begin{aligned} \mathbf{T} : \mathbf{H}(\text{div}; \Omega) \times L^2(\Omega) &\longrightarrow \mathbf{H}(\text{div}; \Omega) \times L^2(\Omega) \\ (\mathbf{p}, u) &\longrightarrow \left(\mathbf{p}, \frac{1}{2}(-u - \sigma^{-1} \text{div } \mathbf{p})\right). \end{aligned}$$

Furthermore, using the estimate (55), it holds that

$$\mathcal{A}_c((\mathbf{p}, u), \mathbf{T}(\mathbf{p}, u)) \geq \min\left((D_+)^{-1}, \frac{\sigma_-}{2\sigma_+^2}\right) \|\mathbf{p}\|_{\mathbf{H}(\text{div}; \Omega)}^2 + \frac{\sigma_-}{2} \|u\|^2 \geq \underline{\alpha} \|(\mathbf{p}, u)\|_{\mathbf{H}(\text{div}; \Omega) \times L^2(\Omega)}^2, \quad (86)$$

with $\underline{\alpha} = \frac{1}{2} \min(2(D_+)^{-1}, \sigma_-(\sigma_+)^{-2}, \sigma_-)$.

There remains to estimate $\|\mathbf{T}\|$. One has

$$\begin{aligned} \|\mathbf{T}(\mathbf{p}, u)\|_{\mathbf{H}(\text{div}; \Omega) \times L^2(\Omega)}^2 &= \|\mathbf{p}\|_{\mathbf{H}(\text{div}; \Omega)}^2 + \frac{1}{4} \|-u - \sigma^{-1} \text{div } \mathbf{p}\|_{L^2(\Omega)}^2 \\ &\leq \|\mathbf{p}\|_{\mathbf{H}(\text{div}; \Omega)}^2 + \frac{1}{4} \left((1+3) \|u\|_{L^2(\Omega)}^2 + \left(1 + \frac{1}{3}\right) (\sigma_-)^{-2} \|\text{div } \mathbf{p}\|_{L^2(\Omega)}^2 \right) \\ &\leq \left(1 + \frac{1}{3} (\sigma_-)^{-2}\right) \|(\mathbf{p}, u)\|_{\mathbf{H}(\text{div}; \Omega) \times L^2(\Omega)}^2, \end{aligned}$$

so that $\|\mathbf{T}\| \leq (1 + \frac{1}{3} (\sigma_-)^{-2})^{1/2}$. Applying (4), we conclude that

$$\|(\mathbf{p}, u)\|_{\mathbf{H}(\text{div}; \Omega) \times L^2(\Omega)} \leq \frac{2(1 + \frac{1}{3} (\sigma_-)^{-2})^{1/2}}{\min(2(D_+)^{-1}, \sigma_-(\sigma_+)^{-2}, \sigma_-)} \|S_f\|_{L^2(\Omega)}.$$

Remark 27. Some of those computations can be found in [28, 41]. Here, we see them as a consequence of the general result stated in Theorem 21. Note that in [28, 41], the T-coercivity estimate (86) is obtained with a constant $\underline{\alpha}' = \frac{1}{2} \min(2(D_+)^{-1}, (\sigma_+)^{-1}, \sigma_-)$, which is very close to $\underline{\alpha}$ since $\sigma_-(\sigma_+)^{-2} = (\sigma_+)^{-1} \cdot \frac{\sigma_-}{\sigma_+}$ and $\frac{\sigma_-}{\sigma_+} \leq 1$.

Remark 28. Here again, the operator T is not unique, see for instance [31, Exercise 56.6] for another possible choice of T-coercive operator with a different weak formulation of Problem (81).

Remark 29. If one wants to obtain estimates without the bounding factors σ_{\pm} and D_{\pm} , a standard path is to imbed the parameters D and σ into the definition of the norms, like it is done in Section 4. Namely, one chooses the norms:

$$\begin{aligned} \|v\|_{\sigma} &= ((\sigma v, v)_{L^2(\Omega)})^{1/2}, \\ \|\mathbf{q}\|_{D^{-1}, \sigma^{-1} \text{div}} &= \left((D^{-1}\mathbf{q}, \mathbf{q})_{L^2(\Omega)} + (\sigma^{-1} \text{div } \mathbf{q}, \text{div } \mathbf{q})_{L^2(\Omega)} \right)^{1/2}, \\ \|(\mathbf{q}, v)\|_V &= \left(\|v\|_{\sigma}^2 + \|\mathbf{q}\|_{D^{-1}, \sigma^{-1} \text{div}}^2 \right)^{1/2}. \end{aligned}$$

On the one hand, all norms are “fixed” once the parameters are given. On the other hand, one can easily check that the stability constant is now independent of the bounding factors, by using the same mapping T as before.

7. T-coercivity at the discrete level

Previously, we demonstrated the robustness and the flexibility of the T-coercivity approach to study mixed problems at the continuous level. In this section, we are going to see how T-coercivity also enables us to provide a stable discretization of such problems with mixed finite elements. Let us recall the simple results below [23, 24].

Definition 30 ([23, Definition 5]). Let W be a Hilbert space, $\mathcal{A}(\cdot, \cdot)$ be a continuous bilinear form over $W \times W$ and $(W_h)_h$ be conforming approximations of W . We say that \mathcal{A} is uniformly T_h -coercive if

$$\exists \alpha^*, \beta^* > 0, \forall h > 0, \exists T_h \in \mathcal{L}(W_h),$$

$$|\mathcal{A}(u_h, T_h u_h)| \geq \alpha^* \|u_h\|_W^2, \quad \forall u_h \in W_h, \quad \text{and} \quad \|T_h\| \leq \beta^*.$$

Proposition 31 ([23, Theorem 2]). Let W be a Hilbert space, f be an element of W' , $\mathcal{A}(\cdot, \cdot)$ be a continuous bilinear form over $W \times W$ and $(W_h)_h$ be conforming approximations of W . Denote by $A_h \in \mathcal{L}(W_h, W_h')$ the discrete operator associated to $\mathcal{A}|_{W_h}$. The problem

$$\begin{cases} \text{Find } u_h \in W_h & \text{such that} \\ \forall v_h \in W_h, & \mathcal{A}(u_h, v_h) = \langle f, v_h \rangle \end{cases}$$

is well-posed and $(A_h^{-1})_h$ is uniformly bounded if and only if \mathcal{A} is uniformly T_h -coercive. In that case, denoting by $C_{\mathcal{A}}$ the continuity constant of the bilinear form \mathcal{A} , it holds that

$$\|u - u_h\|_W \leq C \inf_{v_h \in W_h} \|u - v_h\|_W, \tag{87}$$

with $C = 1 + \frac{C_{\mathcal{A}} \beta^*}{\alpha^*}$ independent of h .

Remark 32. Similarly to Remark 3, it is possible to choose normalized operators $(T_h)_h$ in the above definition, that is $\|T_h\| = 1$, with $\beta^* = 1$ and a value of α^* scaled accordingly. In this case, in the proposition, the constant in (87) writes $C = 1 + C_{\mathcal{A}} (\alpha^*)^{-1}$.

Remark 33. Proposition 31 can be extended to the case where the discrete forms \mathcal{A}_h and f_h differ from the continuous forms \mathcal{A} and f . In that case, Céa's lemma (87) becomes

$$\|u - u_h\|_W \leq C \inf_{v_h \in W_h} (\|u - v_h\|_W + \text{Cons}_{f,h} + \text{Cons}_{\mathcal{A},h}(v_h)),$$

with

$$\text{Cons}_{f,h} = \sup_{v_h \in W_h \setminus \{0\}} \frac{|\langle f - f_h, v_h \rangle|}{\|v_h\|_W}$$

and

$$\text{Cons}_{\mathcal{A},h}(v_h) = \sup_{w_h \in W_h \setminus \{0\}} \frac{|(\mathcal{A} - \mathcal{A}_h)(v_h, w_h)|}{\|w_h\|_W}, \quad \forall v_h \in W_h.$$

As before, we start with the leading example of Stokes problem.

7.1. Stokes problem

For a given h , the natural discretization of Problem (7) reads:

$$\begin{cases} \text{Find } (\mathbf{u}_h, p_h) \in \mathbf{V}_h \times Q_h & \text{such that} \\ \forall (\mathbf{v}_h, q_h) \in \mathbf{V}_h \times Q_h, & \mathcal{A}((\mathbf{u}_h, p_h), (\mathbf{v}_h, q_h)) = \langle \mathbf{f}, \mathbf{v}_h \rangle, \end{cases} \tag{88}$$

where $\mathbf{V}_h \subset \mathbf{H}_0^1(\Omega)$ and $Q_h \subset L_0^2(\Omega)$ are two finite dimensional spaces constituting a conforming approximation of $\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)$.

From Proposition 31, we know that Problem (88) is well-posed if and only if \mathcal{A} is uniformly T_h -coercive. To build a suitable mapping $T_h \in \mathcal{L}(V_h \times Q_h)$, a natural idea is to reproduce the continuous mapping from the proof of Theorem 5

$$T : \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega) \longrightarrow \mathbf{H}_0^1(\Omega) \times L_0^2(\Omega) \\ (\mathbf{u}, p) \longmapsto (\lambda \mathbf{u} + \mathbf{v}_p, -\lambda p)$$

at the discrete level. The operator T above depends on the divergence lifting $\mathbf{v}_p \in \mathbf{H}_0^1(\Omega)$ of the pressure $p \in L_0^2(\Omega)$ defined by, see (5)-(6),

$$-\operatorname{div} \mathbf{v}_p = p \quad \text{and} \quad \|\nabla \mathbf{v}_p\| \leq C_{\operatorname{div}} \|p\|.$$

To obtain a similar lifting in the discrete setting, we consider the continuous lifting of the discrete pressure $p_h \in Q_h \subset L_0^2(\Omega)$, namely $\mathbf{v}_{p_h} \in \mathbf{H}_0^1(\Omega)$ such that

$$-\operatorname{div} \mathbf{v}_{p_h} = p_h \quad \text{and} \quad \|\nabla \mathbf{v}_{p_h}\| \leq C_{\operatorname{div}} \|p_h\|. \tag{89}$$

This lifting \mathbf{v}_{p_h} does not necessarily belong to the discrete space $V_h \subset \mathbf{H}_0^1(\Omega)$, so we need an operator $\Pi_h : \mathbf{H}_0^1(\Omega) \longrightarrow V_h$ to project it on V_h . Therefore, we consider a discrete mapping of the form

$$T_h : V_h \times Q_h \longrightarrow V_h \times Q_h \\ (\mathbf{u}_h, p_h) \longmapsto (\lambda \mathbf{u}_h + \Pi_h(\mathbf{v}_{p_h}), -\lambda p_h). \tag{90}$$

Now, let us precise under which conditions the bilinear form \mathcal{A} is uniformly T_h -coercive by mimicking the proof of Theorem 5. We compute

$$\mathcal{A}((\mathbf{u}_h, p_h), T_h(\mathbf{u}_h, p_h)) = \nu \lambda \|\nabla \mathbf{u}_h\|^2 + \nu \int_{\Omega} \nabla \mathbf{u}_h : \nabla(\Pi_h(\mathbf{v}_{p_h})) \, dx - \int_{\Omega} p_h \operatorname{div}(\Pi_h \mathbf{v}_{p_h}) \, dx.$$

In order to get a term of the form $\|p_h\|^2$, we assume that

$$\int_{\Omega} p_h \operatorname{div}(\Pi_h \mathbf{v}_{p_h}) \, dx = \int_{\Omega} p_h \operatorname{div} \mathbf{v}_{p_h} \, dx, \tag{91}$$

so that

$$\mathcal{A}((\mathbf{u}_h, p_h), T_h(\mathbf{u}_h, p_h)) = \nu \lambda \|\nabla \mathbf{u}_h\|^2 + \nu \int_{\Omega} \nabla \mathbf{u}_h : \nabla(\Pi_h(\mathbf{v}_{p_h})) \, dx + \|p_h\|^2$$

in view of (89). Then, for any $\eta > 0$, Young inequality yields

$$\int_{\Omega} \nabla \mathbf{u}_h : \nabla(\Pi_h(\mathbf{v}_{p_h})) \, dx \geq -\frac{\eta}{2} \|\nabla \mathbf{u}_h\|^2 - \frac{1}{2\eta} \|\nabla(\Pi_h(\mathbf{v}_{p_h}))\|^2 \\ \geq -\frac{\eta}{2} \|\nabla \mathbf{u}_h\|^2 - \frac{C_{\operatorname{div}}^2 C_{\pi}^2}{2\eta} \|p_h\|^2$$

provided that there exists a constant $C_{\pi} > 0$, independent of h and of p_h , such that

$$\|\nabla(\Pi_h(\mathbf{v}_{p_h}))\| \leq C_{\pi} \|\nabla \mathbf{v}_{p_h}\|. \tag{92}$$

Hence, it holds that

$$\mathcal{A}((\mathbf{u}_h, p_h), T_h(\mathbf{u}_h, p_h)) \geq \nu \left(\lambda - \frac{\eta}{2} \right) \|\nabla \mathbf{u}_h\|^2 + \left(1 - \frac{\nu C_{\operatorname{div}}^2 C_{\pi}^2}{2\eta} \right) \|p_h\|^2.$$

Setting $\eta = \lambda = \nu C_{\operatorname{div}}^2 C_{\pi}^2$, we obtain

$$\mathcal{A}((\mathbf{u}_h, p_h), T_h(\mathbf{u}_h, p_h)) \geq \frac{\nu^2 C_{\operatorname{div}}^2 C_{\pi}^2}{2} \|\nabla \mathbf{u}_h\|^2 + \frac{1}{2} \|p_h\|^2 \\ \geq \frac{1}{2} \min(\nu^2 C_{\operatorname{div}}^2 C_{\pi}^2, 1) \|(\mathbf{u}_h, p_h)\|_{\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)}^2. \tag{93}$$

Moreover, taking into account (92) and mimicking the continuous case (see (11)), we have

$$\|T_h\| \leq \max\left(\sqrt{2} \nu C_{\operatorname{div}}^2 C_{\pi}^2, C_{\operatorname{div}} C_{\pi} (2 + \nu^2 C_{\operatorname{div}}^2 C_{\pi}^2)^{1/2}\right). \tag{94}$$

So, with the help of the operator $\Pi_h : \mathbf{H}_0^1(\Omega) \longrightarrow V_h$, we have proven the following result.

Theorem 34. *If there exist a family of operators $(\Pi_h)_h$ and a constant $C_\pi > 0$ such that, for all h ,*

$$\int_\Omega q_h \operatorname{div}(\Pi_h \mathbf{v}) \, dx = \int_\Omega q_h \operatorname{div} \mathbf{v} \, dx, \quad \forall \mathbf{v} \in \mathbf{H}_0^1(\Omega), \forall q_h \in Q_h, \tag{95}$$

$$\|\nabla(\Pi_h(\mathbf{v}))\| \leq C_\pi \|\nabla \mathbf{v}\|, \quad \forall \mathbf{v} \in \mathbf{H}_0^1(\Omega), \tag{96}$$

then Problem (88) is well-posed for all h and

$$\|(\mathbf{u} - \mathbf{u}_h, p - p_h)\|_{\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)} \leq C \inf_{(\mathbf{v}_h, q_h) \in \mathbf{V}_h \times Q_h} \|(\mathbf{u} - \mathbf{v}_h, p - q_h)\|_{\mathbf{H}_0^1(\Omega) \times L_0^2(\Omega)}, \tag{97}$$

with

$$C = 1 + \frac{2 \max(\nu, 2) \max\left(\sqrt{2} \nu C_{\operatorname{div}}^2 C_\pi^2, C_{\operatorname{div}} C_\pi (2 + \nu^2 C_{\operatorname{div}}^2 C_\pi^2)^{1/2}\right)}{\min(\nu^2 C_{\operatorname{div}}^2 C_\pi^2, 1)}.$$

Proof. The previous reasoning shows that the bilinear form \mathcal{A} is uniformly T_h -coercive for the mapping

$$\begin{aligned} T_h : \mathbf{V}_h \times Q_h &\longrightarrow \mathbf{V}_h \times Q_h \\ (\mathbf{u}_h, p_h) &\longmapsto (\nu C_{\operatorname{div}}^2 C_\pi^2 \mathbf{u}_h + \Pi_h(\mathbf{v}_{p_h}), -\nu C_{\operatorname{div}}^2 C_\pi^2 p_h) \end{aligned}$$

as long as the two conditions (91) and (92) are fulfilled for all $p_h \in Q_h$, which is the case if (95) and (96) hold true. The stability estimate (97) then follows by using (93) and (94) in (87). \square

The conditions (95) and (96) correspond exactly to the assumptions of an abstract result known as Fortin's lemma [32]. Above, the T-coercivity approach allowed us to recover these two conditions in a straightforward way. Moreover, we recall that, since the form b fulfills an inf-sup condition (3), those conditions (95)-(96) are equivalent to the so-called *uniform discrete inf-sup condition on the form b*

$$\exists \underline{\beta}' > 0, \quad \forall h, \quad \inf_{q_h \in Q_h \setminus \{0\}} \sup_{\mathbf{v}_h \in \mathbf{V}_h \setminus \{0\}} \frac{\int_\Omega q_h \operatorname{div} \mathbf{v}_h \, dx}{\|\nabla \mathbf{v}_h\| \|q_h\|} \geq \underline{\beta}',$$

see for instance [33, Lemma II.1.1].

Finally, we recall that, provided there is a basic approximability property (i.e. any element of $\mathbf{V} \times Q$ can be approximated by a sequence of elements of $(\mathbf{V}_h \times Q_h)_h$), the convergence of the discrete solutions to the exact one is a consequence of (97).

7.2. Approximation of saddle-point problems

We now derive a *conforming* approximation of the abstract problem (15), starting from the variational expressions (16) or (17), the latter with the form

$$\mathcal{A}((u, p), (v, q)) = a(u, v) + b(v, p) + b(u, q).$$

So, let $(V_h)_h$, resp. $(Q_h)_h$, be two families of finite dimensional subspaces of V , resp. Q . Starting from (16), the discrete variational formulation writes

$$\begin{cases} \text{Find } (u_h, p_h) \in V_h \times Q_h \text{ such that} \\ \forall v_h \in V_h, \quad a(u_h, v_h) + b(v_h, p_h) = \langle f, v_h \rangle_{V', V} \\ \forall q_h \in Q_h, \quad b(u_h, q_h) = \langle g, q_h \rangle_{Q', Q}. \end{cases}$$

While, starting from (17), the *all-in-one* discrete variational formulation writes

$$\begin{cases} \text{Find } (u_h, p_h) \in V_h \times Q_h \text{ such that} \\ \forall (v_h, q_h) \in V_h \times Q_h, \quad \mathcal{A}((u_h, p_h), (v_h, q_h)) = \langle f, v_h \rangle_{V', V} + \langle g, q_h \rangle_{Q', Q}. \end{cases}$$

In abstract form, the *uniform discrete inf-sup condition on the form b* writes

$$\exists \underline{\beta}' > 0, \quad \forall h, \quad \inf_{q_h \in Q_h \setminus \{0\}} \sup_{v_h \in V_h \setminus \{0\}} \frac{b(v_h, q_h)}{\|v_h\|_V \|q_h\|_Q} \geq \underline{\beta}'. \tag{98}$$

Remark 35. We note that if the form \mathcal{A} is *uniformly T_h -coercive* in the sense of Definition 30, then the form b automatically fulfills a uniform discrete inf-sup condition. As a matter of fact, let $q_h \in Q_h \setminus \{0\}$ be given, and introduce $(w_h, r_h) = T_h(0, q_h)$. Using Definition 30 with the test function $(0, q_h)$ leads to

$$|b(w_h, q_h)| \geq \alpha^* \|q_h\|_Q^2 \quad \text{and} \quad \|(w_h, r_h)\|_{V \times Q} \leq \beta^* \|q_h\|_Q.$$

In particular, $w_h \neq 0$, and it follows that

$$\sup_{v_h \in V_h \setminus \{0\}} \frac{b(v_h, q_h)}{\|v_h\|_V \|q_h\|_Q} \geq \frac{b(w_h, q_h)}{\|w_h\|_V \|q_h\|_Q} \geq \alpha^* \frac{\|q_h\|_Q}{\|w_h\|_V} \geq \frac{\alpha^*}{\beta^*}.$$

The condition (98) holds with $\underline{\beta}' = \alpha^* / \beta^* > 0$.

Let us denote by $\Pi_{Q_h} : Q \rightarrow Q_h$ the orthogonal projection operator defined by

$$(\Pi_{Q_h} p, q_h)_Q = (p, q_h)_Q, \quad \forall p \in Q, \forall q_h \in Q_h.$$

We denote by $B_h : V_h \rightarrow Q_h$ the discrete version of the operator B given by $B_h = \Pi_{Q_h} B|_{V_h}$. In other words, we have

$$(B_h v_h, q_h)_Q = (B v_h, q_h)_Q = b(v_h, q_h), \quad \forall (v_h, q_h) \in V_h \times Q_h.$$

With such notations, the straightforward discrete counterpart of Theorem 8 is

Theorem 36. *The following three statements are equivalent:*

- (i) *There exists $\underline{\beta}' > 0$ such that the form b fulfills the uniform discrete inf-sup condition (98).*
- (ii) *For all h , $B_h : (\text{Ker } B_h)^\perp \rightarrow Q_h$ is an isomorphism, and*

$$\|B_h v_h\|_Q \geq \underline{\beta}' \|v_h\|_V, \quad \forall v_h \in (\text{Ker } B_h)^\perp. \tag{99}$$

- (iii) *For all h , there exists an isomorphic operator $L_{B,h} : Q_h \rightarrow (\text{Ker } B_h)^\perp$ such that*

$$B_h(L_{B,h} q_h) = q_h \quad \text{and} \quad \|q_h\|_Q \geq \underline{\beta}' \|L_{B,h} q_h\|_V, \quad \forall q_h \in Q_h. \tag{100}$$

Remark 37. Obviously, this result also holds if the value of the constant in the discrete inf-sup condition on the form b depends on h , i.e. for each h it holds for some $\underline{\beta}'(h) > 0$, with $\lim_{h \rightarrow 0} \underline{\beta}'(h) = 0$. In this case however, getting error estimates can be more intricate.

As mentioned above for the Stokes system, one has the Fortin lemma (cf. [33, Lemma II.1.1]).

Theorem 38. *Assume that the form b fulfills an inf-sup condition (18). The uniform discrete inf-sup condition on the form b (98) holds if, and only if, there exist a family of operators $(\Pi_h)_h$, with $\Pi_h : V \rightarrow V_h$, and a constant $C_\pi > 0$ such that, for all h ,*

$$b(\Pi_h v, q_h) = b(v, q_h), \quad \forall v \in V, \forall q_h \in Q_h, \tag{101}$$

$$\sup_h \|\Pi_h\| \leq C_\pi.$$

Operators $(\Pi_h)_h$ that fulfill conditions (101) are called Fortin operators.

Let us now proceed with the derivation of conditions to ensure that the form \mathcal{A} is uniformly T_h -coercive. As a general rule, the proofs of the results follow very closely the proofs that were given in the exact case. The straightforwardness of the procedure when going from the continuous to the discrete level is one of the main features of the T-coercivity approach. We give next the discrete counterparts of Theorems 9 and 11.

Theorem 39. Assume that the form a is symmetric and positive, that there exists a constant $\alpha' > 0$ such that

$$a(u_h, u_h) \geq \alpha' \|u_h\|_V^2, \quad \forall u_h \in V_h, \tag{102}$$

and that the uniform discrete inf-sup condition (98) on the form b holds true. Then the form \mathcal{A} is uniformly T_h -coercive.

The property (102) is sometimes called the uniform discrete coercivity property.

Proof. Let h be given. We introduce the mapping

$$\begin{aligned} T_h : V_h \times Q_h &\longrightarrow V_h \times Q_h \\ (u_h, p_h) &\longmapsto (\lambda u_h + L_{B,h} p_h, -\lambda p_h). \end{aligned}$$

We then compute

$$\begin{aligned} \mathcal{A}((u_h, p_h), T_h(u_h, p_h)) &= a(u_h, \lambda u_h) + a(u_h, L_{B,h} p_h) + b(\lambda u_h, p_h) + b(L_{B,h} p_h, p_h) - b(u_h, \lambda p_h) \\ &= \lambda a(u_h, u_h) + a(u_h, L_{B,h} p_h) + \|p_h\|_Q^2, \text{ according to (100)-left.} \end{aligned}$$

Because the form a is symmetric and positive, we can apply Young's inequality: for any $\eta > 0$,

$$a(u_h, L_{B,h} p_h) \geq -\frac{\eta}{2} a(u_h, u_h) - \frac{1}{2\eta} a(L_{B,h} p_h, L_{B,h} p_h).$$

According now to (100)-right, we find

$$a(L_{B,h} p_h, L_{B,h} p_h) \leq C_a \|L_{B,h} p_h\|_V^2 \leq C_a (\underline{\beta}')^{-2} \|p_h\|_Q^2.$$

Using assumption (102), if $\lambda - \frac{\eta}{2} > 0$, it follows that

$$\mathcal{A}((u_h, p_h), T_h(u_h, p_h)) \geq \alpha' \left(\lambda - \frac{\eta}{2} \right) \|u_h\|_V^2 + \left(1 - \frac{C_a (\underline{\beta}')^{-2}}{2\eta} \right) \|p_h\|_Q^2.$$

Setting $\eta = \lambda = C_a (\underline{\beta}')^{-2}$ as in the exact case, we infer that

$$\mathcal{A}((u_h, p_h), T_h(u_h, p_h)) \geq \frac{1}{2} \min \left(\alpha' C_a (\underline{\beta}')^{-2}, 1 \right) \|(u_h, p_h)\|_{V \times Q}^2$$

which proves that \mathcal{A} is T_h -coercive, with a T -coercivity constant $\frac{1}{2} \min(\alpha' C_a (\underline{\beta}')^{-2}, 1) > 0$ that is independent of h .

Since $T_h(u_h, p_h) = (C_a (\underline{\beta}')^{-2} u_h + L_{B,h} p_h, -C_a (\underline{\beta}')^{-2} p_h)$, one finds that

$$\begin{aligned} \|T_h(u_h, p_h)\|_{V \times Q}^2 &\leq 2 \left(C_a (\underline{\beta}')^{-2} \right)^2 \|u_h\|_V^2 + 2 \|L_{B,h} p_h\|_V^2 + \left(C_a (\underline{\beta}')^{-2} \right)^2 \|p_h\|_Q^2 \\ &\leq 2 \left(C_a (\underline{\beta}')^{-2} \right)^2 \|u_h\|_V^2 + \left(2 (\underline{\beta}')^{-2} + \left(C_a (\underline{\beta}')^{-2} \right)^2 \right) \|p_h\|_Q^2, \end{aligned}$$

where the last inequality follows from (100)-right. The bound is valid for all h , which yields

$$\sup_h \|T_h\| \leq \max \left(\sqrt{2} C_a (\underline{\beta}')^{-2}, \beta (2 + C_a^2 (\underline{\beta}')^{-2})^{1/2} \right),$$

so the form \mathcal{A} is uniformly T_h -coercive. □

Remark 40. As for the Stokes problem, the discrete right-inverse $L_{B,h}$ is connected to the Fortin operator Π_h . As a matter of fact, if there exists a family of discrete projectors $(\Pi_h)_h$ verifying (101), the operator defined by $L_{B,h} = \Pi_h(L_B)$ satisfies (100) with $\underline{\beta}' = (C_\pi \beta)^{-1}$ since for all $q_h \in Q_h$

$$\|\Pi_h(L_B q_h)\|_V \leq C_\pi \|L_B q_h\|_V \leq C_\pi \beta \|q_h\|_Q,$$

according to (22). As a consequence, to perform stability estimates at the discrete level using T_h -coercivity, one has only to replace β by $C_\pi \beta$ in the computations done at the continuous level.

Theorem 41. Assume that the form a is symmetric and positive.

In this case, if the uniform discrete inf-sup condition (98) on the form b holds true and if there exists a constant $\alpha'_0 > 0$ such that

$$a(u_{0,h}, u_{0,h}) \geq \alpha'_0 \|u_{0,h}\|_V^2, \quad \forall u_{0,h} \in \text{Ker } B_h, \tag{103}$$

then the form \mathcal{A} is uniformly T_h -coercive.

The property (103) is sometimes called the uniform discrete coercivity property on the kernels.

Proof. Let h be given. We consider the mapping

$$\begin{aligned} T_h : V_h \times Q_h &\longrightarrow V_h \times Q_h \\ (u_h, p_h) &\longmapsto (\lambda u_h + L_{B,h} p_h, -\lambda p_h + \lambda \mu B_h u_h). \end{aligned}$$

As in the proof of Theorem 11, we can compute

$$\mathcal{A}((u_h, p_h), T_h(u_h, p_h)) = \lambda a(u_h, u_h) + a(u_h, L_{B,h} p_h) + \|p_h\|_Q^2 + \lambda \mu \|B_h u_h\|_Q^2$$

because $b(L_{B,h} p_h, p_h) = \|p_h\|_Q^2$. Since the form a is symmetric and positive, one may use Young's inequality. By proceeding as in the proof of Theorem 39 and after setting $\lambda = C_a(\underline{\beta}')^{-2}$, we find that

$$\lambda a(u_h, u_h) + a(u_h, L_{B,h} p_h) + \|p_h\|_Q^2 \geq \frac{1}{2} C_a (\underline{\beta}')^{-2} a(u_h, u_h) + \frac{1}{2} \|p_h\|_Q^2,$$

and

$$\mathcal{A}((u_h, p_h), T_h(u_h, p_h)) \geq \frac{1}{2} C_a (\underline{\beta}')^{-2} (a(u_h, u_h) + 2\mu \|B_h u_h\|_Q^2) + \frac{1}{2} \|p_h\|_Q^2.$$

Then, we use the decomposition $u_h = u_{0,h} + \bar{u}_h$ with $u_{0,h} \in \text{Ker } B_h$ and $\bar{u}_h \in (\text{Ker } B_h)^\perp$. As before, Young's inequality yields

$$a(u_h, u_h) \geq (1 - \theta) a(u_{0,h}, u_{0,h}) + \left(C_a - \frac{C_a}{\theta} \right) \|\bar{u}_h\|_V^2$$

for all $0 < \theta < 1$. Moreover, $\|B_h u_h\|_Q^2 = \|B_h \bar{u}_h\|_Q^2 \geq (\underline{\beta}')^2 \|\bar{u}_h\|_V^2$ according to (99), so that

$$a(u_h, u_h) + 2\mu \|B_h u_h\|_Q^2 \geq (1 - \theta) a(u_{0,h}, u_{0,h}) + \left(C_a - \frac{C_a}{\theta} + 2\mu (\underline{\beta}')^2 \right) \|\bar{u}_h\|_V^2.$$

Choosing $\theta = \frac{1}{2}$ and $\mu = \frac{3}{4} C_a (\underline{\beta}')^{-2}$, it holds that

$$\begin{aligned} a(u_h, u_h) + 2\mu \|B_h u_h\|_Q^2 &\geq \frac{1}{2} a(u_{0,h}, u_{0,h}) + \frac{C_a}{2} \|\bar{u}_h\|_V^2 \\ &\geq \frac{\alpha'_0}{2} \|u_{0,h}\|_V^2 + \frac{\alpha'_0}{2} \|\bar{u}_h\|_V^2 = \frac{\alpha'_0}{2} \|u_h\|_V^2, \end{aligned}$$

where we used assumption (103) and $C_a \geq \alpha'_0$ on the second line.

Finally, we conclude that

$$\mathcal{A}((u_h, p_h), T_h(u_h, p_h)) \geq \frac{1}{4} \alpha'_0 C_a (\underline{\beta}')^{-2} \|u_h\|_V^2 + \frac{1}{2} \|p_h\|_Q^2,$$

which yields that \mathcal{A} is T_h -coercive, with a T-coercivity constant $\min(\frac{1}{4} \alpha'_0 C_a (\underline{\beta}')^{-2}, \frac{1}{2}) > 0$ that is independent of h .

From the above, we have $T_h(u_h, p_h) = (C_a(\underline{\beta}')^{-2} u_h + L_{B,h} p_h, -C_a(\underline{\beta}')^{-2} p_h + \frac{3}{4} (C_a(\underline{\beta}')^{-2})^2 B_h u_h)$, and, noting that $\|B_h u_h\|_Q \leq C_b \|u_h\|_V$, one concludes that

$$\sup_h \|T_h\| \leq \infty,$$

so the form \mathcal{A} is uniformly T_h -coercive. □

Remark 42. The reciprocal of Theorem 41 is also true. To see this, one simply needs to mimick the proof of Theorem 11 - item 2. at the discrete level.

Again, provided a basic approximability property holds, that is, any element of $V \times Q$ can be approximated by a sequence of elements of $(V_h \times Q_h)_h$, convergence will follow under the assumptions of Theorem 39 or Theorem 41.

7.3. Approximation of augmented saddle-point problems

We now approximate the abstract problem (36), starting from the variational expression (37), with the form

$$\mathcal{A}_c((u, p), (v, q)) = a(u, v) + b(v, p) + b(u, q) - c(p, q),$$

where $c(\cdot, \cdot)$ is a form defined on $Q \times Q$ that fulfills (35); in particular, $c(\cdot, \cdot)$ is positive. So, let again $(V_h)_h$, resp. $(Q_h)_h$, be two families of finite dimensional subspaces of V , resp. Q . The discrete variational formulation writes

$$\begin{cases} \text{Find } (u_h, p_h) \in V_h \times Q_h & \text{such that} \\ \forall (v_h, q_h) \in V_h \times Q_h, & \mathcal{A}_c((u_h, p_h), (v_h, q_h)) = \langle f, v_h \rangle_{V',V} + \langle g, q_h \rangle_{Q',Q}, \end{cases}$$

To ensure that the form \mathcal{A}_c is uniformly T_h -coercive, the proofs once more follow very closely those that were given in the exact case. We give next the discrete counterparts of Theorems 13, 15 and 21.

Theorem 43. *Assume that the form a is symmetric, positive, fulfills the uniform discrete coercivity property (102), and that the uniform discrete inf-sup condition (98) on the form b holds true. Then the form \mathcal{A}_c is uniformly T_h -coercive.*

Theorem 44. *Assume that the form a is symmetric and positive, fulfills the uniform discrete coercivity property on the kernels (103), and that the uniform discrete inf-sup condition (98) on the form b holds true. If moreover the form c is like in (40), where ε is small enough, namely*

$$\varepsilon \leq \frac{1}{2C_a(C_\pi\beta)^4 C_b^2} \left(2 - \frac{\alpha'_0}{C_a}\right),$$

then the form \mathcal{A}_c is uniformly T_h -coercive.

Theorem 45. *Assume that (51) holds true and that the bilinear forms a and c are both symmetric and positive. If there exists a constant $\alpha'_B > 0$ such that*

$$a(u_h, u_h) + \frac{\gamma}{2C_c^2} \|B_h u_h\|_Q^2 \geq \alpha'_B \|u_h\|_V^2, \quad \forall u_h \in V_h, \tag{104}$$

then the form \mathcal{A}_c is uniformly T_h -coercive.

As before, provided a basic approximability property holds, that is, any element of $V \times Q$ can be approximated by a sequence of elements of $(V_h \times Q_h)_h$, convergence will follow under the assumptions of Theorem 43, Theorem 44 or Theorem 45.

7.4. Applications

Let us briefly see how the T-coercivity approach can be used to discretize the mixed problems, that is for Stokes, electromagnetism, nearly-incompressible elasticity and finally neutron diffusion. For each problem, we propose one or several possibilities. Note that, since there is a vast litterature on this topic, there is no need to devise new approximation techniques. On the contrary, the simple framework of the T-coercivity approach provides elementary guidelines to help us choose among existing techniques. In most cases, we emphasize that this leads to explicit discrete operators T_h . And, as we shall see next, the degree of explicitness depends on the problem that is studied.

In each case, the first step is to choose a *conforming* finite element discretization adapted to the space V under consideration. We assume for simplicity that Ω is a polyhedron for $d = 3$, or a polygon for $d = 2$, so one can use meshes made of simplices for the discretization by finite elements. For $k \geq 1$, \mathcal{P}_k stands for the Lagrange finite elements of order k . For Stokes and elasticity, we note that the space $\mathbf{H}_0^1(\Omega)$ may be approximated using $(\mathcal{P}_k)^d$ finite elements with $k \geq 2$. For electromagnetism, we have to deal with the space $\mathbf{H}_0(\mathbf{curl}; \Omega)$, which can be discretized using the (first-kind) Nédélec finite elements of order $k \geq 1$, denoted by \mathcal{N}_k . Lastly, for neutron diffusion, we have to deal with the space $\mathbf{H}(\text{div}; \Omega)$, discretized with the help of the Raviart–Thomas elements of order $k \geq 0$, denoted by \mathcal{RT}_k . We refer to [5] for details.

The next step is to choose the *conforming* finite element discretization in the space Q in such a way that convergence of the discrete solutions to the exact one is guaranteed. This occurs as soon as one achieves uniform T_h -coercivity for the all-in-one form \mathcal{A} . To that aim, one simply has to build discrete operators T_h similarly as in the continuous case but using (when applicable) the Fortin operators defined in Theorem 38 to project the lifting L_B on the discrete space. Note that according to classical theory [5, 33], the existence of such operators is equivalent to the uniform discrete inf-sup condition (98) on the form b . Doing so, the discrete stability estimates then follow from the continuous case by changing the constant β to take into account the influence of the Fortin operators, see Remark 40.

First, for Stokes and elasticity, and for $k = 2$, setting $Q_h = \mathcal{P}_1$ leads to Fortin operators $\Pi_h^{\mathcal{P}} : \mathbf{H}_0^1(\Omega) \rightarrow (\mathcal{P}_k)^d$ satisfying (95)–(96), or the abstract counterpart (101): the pair $((\mathcal{P}_2)^d, \mathcal{P}_1)$ is called the Taylor–Hood finite element. In this case, building Fortin operators is a very technical issue. We do not go into the details, and refer instead to [5, Section 8.8]: we note that the resulting expression of the operator $\Pi_h^{\mathcal{P}}$ is quite involved. This leads to a uniform discrete inf-sup condition on the form b . Regarding uniform T_h -coercivity, one uses (90) to define the discrete operators T_h for Stokes. While, for nearly-incompressible elasticity, the bilinear form defined in (79) is uniformly T_h -coercive for the mapping

$$T_h : (\mathcal{P}_2)^d \times \mathcal{P}_1 \rightarrow (\mathcal{P}_2)^d \times \mathcal{P}_1$$

$$(\mathbf{u}_h, p_h) \mapsto \left(2\mu (C_{\pi, \mathcal{P}} C_{\text{div}})^2 \mathbf{u}_h + \Pi_h^{\mathcal{P}}(\mathbf{v}_{-p_h}), -2\mu (C_{\pi, \mathcal{P}} C_{\text{div}})^2 p_h \right),$$

according to Theorem 43 and (80).

For electromagnetism in an anisotropic medium (with smooth tensor fields $\underline{\varepsilon}$ and $\underline{\mu}$), for $k \geq 1$, setting $Q_h = \mathcal{P}_k$ leads to Fortin operators $\Pi_h^{\mathcal{N}} : \mathbf{H}_0(\mathbf{curl}; \Omega) \rightarrow \mathcal{N}_k$ satisfying (101). Let us explain below how to proceed. In (101), the operators must fulfill the compatibility conditions

$$\left(\underline{\varepsilon} \Pi_h^{\mathcal{N}} \mathbf{v}, \nabla q_h \right)_{L^2(\Omega)} = \left(\underline{\varepsilon} \mathbf{v}, \nabla q_h \right)_{L^2(\Omega)}, \quad \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \quad \forall q_h \in \mathcal{P}_k. \quad (105)$$

Under the assumptions (56) on $\underline{\varepsilon}$ (and $\underline{\mu}$), the Helmholtz decomposition of \mathbf{v} , orthogonal with respect to the inner product $(\cdot, \cdot)_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}$, writes $\mathbf{v} = \mathbf{k}_v + \nabla \phi_v$, where $\mathbf{k}_v \in \mathbf{K}_N(\Omega; \underline{\varepsilon})$ and $\phi_v \in H_0^1(\Omega)$ solves (74). Since $q_h \in H_0^1(\Omega)$, we note that

$$\left(\underline{\varepsilon} \mathbf{v}, \nabla q_h \right)_{L^2(\Omega)} = \left(\underline{\varepsilon} \nabla \phi_v, \nabla q_h \right)_{L^2(\Omega)}, \quad \forall \mathbf{v} \in \mathbf{H}_0(\mathbf{curl}; \Omega), \quad \forall q_h \in \mathcal{P}_k.$$

This leads to the “natural” choice

$$\Pi_h^{\mathcal{N}} \mathbf{v} = \nabla \left(P_h^k \phi_v \right),$$

where $P_h^k : H_0^1(\Omega) \rightarrow \mathcal{P}_k$ is the orthogonal projection on \mathcal{P}_k with respect to the inner product $(\cdot, \cdot)_{1, \underline{\varepsilon}}$, namely

$$\left(\underline{\varepsilon} \nabla \left(P_h^k \phi \right), \nabla q_h \right)_{L^2(\Omega)} = \left(\underline{\varepsilon} \nabla \phi, \nabla q_h \right)_{L^2(\Omega)}, \quad \forall \phi \in H_0^1(\Omega), \quad \forall q_h \in \mathcal{P}_k. \quad (106)$$

Indeed, the above problem is well-posed thanks to the assumptions (56) on $\underline{\varepsilon}$, and $\Pi_h^{\mathcal{N}} \mathbf{v}$ automatically belongs to \mathcal{N}_k because, by design, the finite element space \mathcal{N}_k contains $\nabla[\mathcal{P}_k]$.

With this definition of the operator $\Pi_h^{\mathcal{N}}$, the compatibility conditions (105) immediately follow. Furthermore, the uniform bound on the norm of the operators in (101) is obtained via

$$\begin{aligned} \left\| \Pi_h^{\mathcal{N}} \boldsymbol{\nu} \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 &= \left\| \nabla \left(P_h^k \phi_{\boldsymbol{\nu}} \right) \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}^2 \\ &= \left(\underline{\varepsilon} \nabla \left(P_h^k \phi_{\boldsymbol{\nu}} \right), \nabla \left(P_h^k \phi_{\boldsymbol{\nu}} \right) \right)_{L^2(\Omega)} \\ \text{(cf. (106))} &= \left(\underline{\varepsilon} \nabla \phi_{\boldsymbol{\nu}}, \nabla \left(P_h^k \phi_{\boldsymbol{\nu}} \right) \right)_{L^2(\Omega)} \\ &\leq \left\| \nabla \phi_{\boldsymbol{\nu}} \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \left\| \nabla \left(P_h^k \phi_{\boldsymbol{\nu}} \right) \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \\ &= \left\| \nabla \phi_{\boldsymbol{\nu}} \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \left\| \Pi_h^{\mathcal{N}} \boldsymbol{\nu} \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}, \end{aligned}$$

so that $\left\| \Pi_h^{\mathcal{N}} \boldsymbol{\nu} \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}} \leq \left\| \boldsymbol{\nu} \right\|_{\underline{\varepsilon}, \underline{\mu}^{-1} \mathbf{curl}}$ by orthogonality of the Helmholtz decomposition.

On the other hand, the uniform coercivity condition on the discrete kernels in Theorem 41 is obtained for instance in [25, Theorem 3]. It hinges on the crucial property stating that, given a field $\boldsymbol{\nu} = \nabla q$ with $q \in H_0^1(\Omega)$, the result of the interpolation of $\boldsymbol{\nu}$ with the Nédélec interpolation operator may be expressed as ∇q_h for some $q_h \in \mathcal{P}_k$.

Hence, for electromagnetism in an anisotropic medium we infer from Theorem 41 that the bilinear form $\mathcal{A}_{\underline{\varepsilon}, \underline{\mu}}$ defined in (69) is uniformly T_h -coercive for the mapping

$$\begin{aligned} T_h : \mathcal{N}_k \times \mathcal{P}_k &\longrightarrow \mathcal{N}_k \times \mathcal{P}_k \\ (\boldsymbol{E}_h, \tilde{p}_h) &\longmapsto \left((C_{\pi, \mathcal{N}})^2 \boldsymbol{E}_h + \Pi_h^{\mathcal{N}} (\nabla \tilde{p}_h), - (C_{\pi, \mathcal{N}})^2 \tilde{p}_h + \frac{3}{4} (C_{\pi, \mathcal{N}})^4 \phi_{\boldsymbol{E}_h} \right), \end{aligned}$$

where $\phi_{\boldsymbol{E}_h} \in Q_h$ satisfies the discrete counterpart of (74), namely

$$\left(\underline{\varepsilon} \nabla \phi_{\boldsymbol{E}_h}, \nabla q_h \right)_{L^2(\Omega)} = \left(\underline{\varepsilon} \boldsymbol{E}_h, \nabla q_h \right)_{L^2(\Omega)}, \quad \forall q_h \in \mathcal{P}_k.$$

Alternatively, one can follow Section 4.2. In this case, adding indices and superscripts h in the definition of T_{opt} , one considers

$$\begin{aligned} (T_{opt})_h : \mathcal{N}_k \times \mathcal{P}_k &\longrightarrow \mathcal{N}_k \times \mathcal{P}_k \\ (\boldsymbol{E}_h, \tilde{p}_h) &\longmapsto \left(\boldsymbol{k}_{\boldsymbol{E}_h}^h + \nabla \tilde{p}_h, \phi_{\boldsymbol{E}_h}^h \right), \end{aligned}$$

with the decomposition $\boldsymbol{E}_h = \boldsymbol{k}_{\boldsymbol{E}_h}^h + \nabla \phi_{\boldsymbol{E}_h}^h$. The crucial idea is now to use a discrete Helmholtz decomposition to define $\boldsymbol{k}_{\boldsymbol{E}_h}^h$ and $\phi_{\boldsymbol{E}_h}^h$. Namely, for $\boldsymbol{v}_h \in \mathcal{N}_k$, $\phi_{\boldsymbol{v}_h}^h \in \mathcal{P}_k$ is defined by

$$\left(\underline{\varepsilon} \nabla \phi_{\boldsymbol{v}_h}^h, \nabla q_h \right)_{L^2(\Omega)} = \left(\underline{\varepsilon} \boldsymbol{v}_h, \nabla q_h \right)_{L^2(\Omega)}, \quad \forall q_h \in \mathcal{P}_k,$$

and $\boldsymbol{k}_{\boldsymbol{v}_h}^h = \boldsymbol{v}_h - \nabla \phi_{\boldsymbol{v}_h}^h$. Doing so, one obtains an (orthogonal) discrete Helmholtz decomposition that is uniformly stable, and it can be checked that the form $\mathcal{A}_{\underline{\varepsilon}, \underline{\mu}}$ is uniformly T_h -coercive. The results also hold for piecewise smooth tensor fields $\underline{\varepsilon}$ and $\underline{\mu}$. Details can be found in [25, Proposition 13].

Last, for neutron diffusion, we use $Q_h = \mathcal{P}_k^{pw}$, for $k \geq 0$, where the superscript pw stands for piecewise Lagrange finite elements of order k . Assuming for simplicity that σ restricted to any simplex is constant, we introduce the discrete mapping [28, 41]

$$\begin{aligned} T_h : \mathcal{RT}_k \times \mathcal{P}_k^{pw} &\longrightarrow \mathcal{RT}_k \times \mathcal{P}_k^{pw} \\ (\boldsymbol{p}_h, u_h) &\longmapsto \left(\boldsymbol{p}_h, \frac{1}{2} (-u_h + \sigma^{-1} \operatorname{div} \boldsymbol{p}_h) \right), \end{aligned}$$

and the property $\operatorname{div}(\mathcal{RT}_k) \subset \mathcal{P}_k^{pw}$ guarantees the uniform T_h -coercivity of the bilinear form (85) in virtue of Theorem 45.

All basic approximability properties are established in [5], which guarantees convergence in all of the above cases. We again refer to [5] for details and possible extensions, such as the generalized Taylor–Hood elements ($k \geq 3$) or the MINI element for Stokes or elasticity.

8. Conclusion and perspectives

We have demonstrated the flexibility of the T-coercivity approach, here applied to classical linear mixed problems, both for the theoretical study of the problems and for their numerical approximation by finite elements. Let us mention some possible extensions, such as nonconforming discretization methods for Stokes [40], multigroup diffusion [34] or DDM for diffusion [28]. It is our belief that numerous applications can be studied with the T-coercivity approach, both theoretically and numerically. Recent works include application in poromechanics [3, 4], time-harmonic Maxwell’s equations with impedance surfaces [43], and the applications listed in [39].

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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