JEAN-LUC GUERMOND

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SOME IMPLEMENTATIONS OF PROJECTION METHODS FOR NAVIER-STOKES EQUATIONS (*)

by Jean-Luc GUERMOND (*)

Abstract — This paper is concerned with the implementation of spatially discrete versions of Chorin-Temam’s projection methods. The emphasis is put on the projection step, which enforces incompressibility. Three types of variational approximations are reviewed. In the first one, the projection step is solved as a div-grad problem with velocity test functions satisfying (at first glance) a paradoxical Dirichlet condition. In the second method, the projection step is still solved as a div-grad problem but the velocity test functions satisfy a boundary condition only for the normal component. In the third approach the projection step is solved in the form of a Poisson equation supplemented with a Neumann boundary condition. The first method is shown to be legitimate and economical for finite element approximations, whereas the second one is shown to be useful for spectral approximations. The third one is probably the easiest to implement since it avoids the problem of the mass matrix occurring in the two others. Though the second and third approaches do not directly involve a inf-sup condition, this condition is pointed out to be necessary to establish convergence and rule out possible spurious pressure. Finally some links between these algorithms and some preconditioning techniques of the Uzawa operator are shown.

Key words: Projection method, Fractional step method, Navier-Stokes equations.

Résumé — Dans cet article on s'intéresse a quelques approximations spatiales des méthodes de projections du type Chorin-Temam. On s'intéresse plus particulièrement à l'étape de projection, qui vise à imposer l'incompressibilité. Trois types d'approximations variationnelles sont étudiées. Dans la première on résout l'étape de projection sous la forme d'un problème de Darcy avec des vitesses test satisfaisant une condition de Dirichlet (à première vue) paradoxale. Dans la seconde approche, le problème est encore résolu sous sa forme div-grad (le Darcy) mais les vitesses test n'ont cette fois-ci une condition à la frontière portant uniquement sur la composante normale. Dans la troisième méthode, l'étape de projection est résolue sous la forme d'une équation de Poisson avec une condition de Neumann. On montre que la première méthode est légitime pour des approximations par éléments finis, alors que la seconde a de l'intérêt aussi pour des approximations spectrales. La troisième méthode est probablement la plus aisée à mettre en œuvre puisque qu'elle permet d'éviter l'inversion d'une matrice de masse qui est obligatoire pour les deux autres. Bien que les deux dernières méthodes n'imposent pas directement de compatibilité entre les espaces de vitesse et de pression, on montre qu'une telle condition est nécessaire pour assurer la convergence de la méthode. Finalement on montre quelques liens entre ces algorithmes et certaines techniques de préconditionnement de l'opérateur d’Uzawa.

AMS(MOS) subject classifications: 35A40, 35Q30, 65J15

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(1) Laboratoire d'Informatique pour la Mécanique et les Sciences de l'Ingénieur, C N R S, BP 133, 91403, Orsay, France (guermond@limsi.fr)
1. INTRODUCTION

In this paper we consider discrete approximations of a class of fractional step techniques known as Chorin-Temam projection methods [8] [23]. These techniques have been proposed for approximating in time the unsteady incompressible Navier-Stokes equations. They are devised to turn around the coupling between the pressure and the velocity that is implied by the incompressibility constraint: \( \text{div} \, u = 0 \). The basic idea consists in devising time marching procedures that uncouple viscous and incompressibility effects. These techniques are very efficient and have probably been the first numerical schemes enabling a cost-effective solution of three-dimensional time-dependent problems (cf. Quartapelle [19, p 177]). Their simplicity and sometimes surprising efficiency render them particularly attractive to the CFD community (see e.g. [2], [9], [11], [12], [25]). Although these techniques have long been used for calculating steady-state solutions to Navier-Stokes equations, they are now regaining their status as true time marching procedures for calculating time-dependent incompressible viscous flows. This renewed interest for time-dependent solutions to Navier-Stokes equations is prompted by the increasing capacities of computers and the success of large eddy theories which recognize that unsteadiness of large eddies should be well predicted whereas smaller scales can (reasonably) be filtered.

Since its initial appearance, the projection method has been implemented with various types of spatial approximations and the fractional step has been modified in order to improve the overall accuracy of the scheme. Though the stability of this method and its modified versions can generally be proven quite easily when space variables are continuous, the stability and convergence of their discrete counterparts are often overlooked in the literature.

For instance, the projection step may be put into two different forms. One possibility consists in solving a so-called div-grad or Darcy problem as follows

\[
\begin{align*}
\frac{u + \delta t \text{ \nabla} \phi}{\nabla} &= \bar{u} \\
\nabla \cdot u &= 0 \\
\frac{u}{n} \big|_{\partial \Omega} &= 0
\end{align*}
\]

(1.1)

The second possibility consists in obtaining from (1.1) a Poisson equation supplemented with a homogeneous Neumann boundary condition on the pressure

\[
\begin{align*}
\nabla^2 \phi &= \frac{\nabla \cdot \bar{u}}{\delta t} \\
\frac{\partial \phi}{\partial n} \big|_{\partial \Omega} &= 0.
\end{align*}
\]

(1.2)
Although (1.1) and (1.2) are equivalent in some sense, their discrete counterparts are not in general. On the one hand, discrete variational approximations of the Darcy problem yield pressure equations of type $\mathcal{B}_h \mathcal{J}_h^{-1} \mathcal{B}_h^T \Phi = F$, where $\mathcal{J}_h$ is a mass matrix and $\mathcal{B}_h$ is a matrix associated with the divergence operator. In this case the homogeneous Neumann boundary condition on the pressure is not enforced, though it is implicitly accounted for by the velocity tests functions which have the normal component vanishing at the boundary. On the other hand, discrete variational approximations of (1.2) yield equations of type $\mathcal{D}_h \Phi = F$, where $\mathcal{D}_h$ is an approximation of the Laplace operator and the homogeneous Neumann boundary condition is explicitly, though weakly, enforced by the variational formulation. At this point, one may ask oneself which procedure is correct? If both are correct what are their respective range of application? It is shown in this paper that both approaches are correct, and each of them has its own advantages within its respective functional framework.

The other point that is discussed in this paper concerns the appropriate boundary condition that should be imposed on the end-of-step velocity. Thanks to theorem 2.1 (see below), it is clear on (1.1) that, as far as the spatially continuous problem is concerned, only the normal component of the end-of-step velocity should be constrained. However, when the problem is discretized in space, the answer is no longer clear: a full Dirichlet condition on the end-of-step velocity is sometimes advocated by some authors (cf. e.g. Gresho and Chan [12, part II]), whereas other authors impose a, more natural, condition on the normal component of the velocity (cf. Donea et al. [9], Azaiez et al. [1]). Which solution is correct? What are their respective advantages? It is the purpose of this paper to show that both solutions are suitable if applied in the correct functional frameworks. Actually, we show in this paper that the intermediate velocity and the final velocity should be approximated in two different spaces.

This paper is organized as follows. In § 2, we review non incremental and incremental projection schemes in the space continuum. In § 3, we analyze a discrete projection scheme in which the provisional velocity and the corrected one are approximated in the same space; that is, the end-of-step velocity satisfies a Dirichlet condition. This scheme is shown to be efficient for finite element approximations. A discrete projection scheme with an approximation space enforcing a boundary condition only on the normal component of the end-of-step velocity is analyzed in § 4. This functional framework is shown to be useful for spectral approximations. In § 5, the projection step is formulated as a Poisson problem supplemented with a Neumann boundary condition. This technique is probably the easiest to implement, for it turns around a mass matrix problem that plagues the two others. Some generalization and convergence results are presented in § 6. In § 7, we show that the three projection
algorithms are, in some sense, equivalent to some known preconditioning techniques of the Uzawa operator for which the preconditioner is applied only once.

2. PRELIMINARIES

2.1. The continuous unsteady Stokes problem

In this paper we consider numerical approximations with respect to time and space of the time-dependent Navier-Stokes equations formulated in the primitive variables, namely velocity and pressure. However, to simplify the presentation and since we are mainly concerned with the parabolic aspect of the problem, we restrict ourselves to the time-dependent Stokes problem

\[
\begin{align*}
\frac{\partial u}{\partial t} - \nabla^2 u + \nabla p &= f \\
\nabla \cdot u &= 0 \\
u_{|\partial \Omega} &= 0 \\
u_{|t=0} &= v_0,
\end{align*}
\]  

(2.1)

where \( f(t) \) is a body force, and the boundary condition on the velocity is set to zero for sake of simplicity. The fluid domain \( \Omega \) is open connected and bounded in \( \mathbb{R}^d \) (\( d = 2 \) or \( 3 \) in practical applications). The domain boundary \( \partial \Omega \) is assumed to be smooth, say \( \partial \Omega \) is Lipschitz and \( \Omega \) is locally on one side of its boundary.

In the following we work within the classical framework of the Sobolev spaces. The set of real functions infinitely differentiable with compact support in \( \Omega \) is denoted by \( \mathcal{D}(\Omega) \), and the set of distributions on \( \Omega \) is denoted by \( \mathcal{D}'(\Omega) \). As usual, \( L^2(\Omega) \) denotes the space of real-valued functions the squares of which are summable in \( \Omega \). The inner product in \( L^2(\Omega) \) is denoted by \( \langle \cdot, \cdot \rangle \) and \( | \cdot |_0 \) is the associated norm. We identify \( L^2(\Omega) \) with its dual \( \mathcal{H}^m(\Omega), m \geq 0 \), is the set of distributions the successive derivatives of which, up to order \( m \), can be identified with square summable functions. The space \( \mathcal{H}^m(\Omega) \), equipped with the norm

\[
|u|^2_m = \left( \sum_{|\alpha| = 0}^m |D^\alpha u|^2 \right)^{1/2},
\]

expressed in the multi-index notation, is a Hilbert space [18]. We define \( \mathcal{H}^m_0(\Omega) \) as the completion of \( \mathcal{D}(\Omega) \) in \( \mathcal{H}^m(\Omega) \), and we denote \( \mathcal{H}^{-m}(\Omega) \) the dual of \( \mathcal{H}^m(\Omega) \).
The incompressibility condition on the velocity leads to consider solenoidal vector fields. For this reason, we define \( N(\Omega) = \{ v \in D(\Omega), \nabla \cdot v = 0 \} \), and we denote by \( H \) and \( V \) the completions of \( N(\Omega) \) in \( L^2(\Omega)^d \) and \( H_0^1(\Omega)^d \), respectively. Spaces \( H \) and \( V \) are characterized by:

\[
H = \{ v \in L^2(\Omega)^d, \nabla \cdot v = 0, v \cdot n_{|\partial\Omega} = 0 \},
\]

\[
V = \{ v \in H^1(\Omega)^d, \nabla \cdot v = 0, v_{|\partial\Omega} = 0 \}.
\]

See for instance Temam [22, pp. 15-18] for a proof. In the following, the space \( H \) plays an important role by means of

**Theorem 2.1:** Under the hypotheses on \( \Omega \) stated above, we have the orthogonal decomposition

\[
L^2(\Omega)^d = H \oplus V(H^1(\Omega)/\mathbb{R}).
\]

**Proof:** See for instance Girault and Raviart [10].

If one assumes that \( f \in L^2(0, T; H^{-1}(\Omega)^d) \) and \( u_0 \in H \), then it is well-known that (2.1) is well-posed (look for \( u \in L^2(0, T, V) \cap C^0(0, T; H) \) and restrict the time evolution problem to \( L^2(0, T; V') \) where \( V' \) is the dual of \( V \) and apply Lions’s theorem [18, p. 257]). Furthermore, one may verify that \( p \in L^2(0, T; L^2(\Omega)/\mathbb{R}) \). It is hereafter assumed that the data are regular enough and satisfy all the compatibility conditions that are needed for a smooth solution to exist.

We now turn the attention to the time approximation of (2.1) by means of projection methods. To make the presentation self-contained, we begin by recalling the main features of some projection schemes.

### 2.2. The non-incremental and incremental projection schemes

Projection methods have been introduced by Chorin [8] and Temam [23]. They are time marching procedures based on a fractional step technique that may be viewed also as a predictor-corrector strategy aiming at uncoupling viscous diffusion and incompressibility effects. The time interval \([0, T]\) on which the solution is sought is partitioned into \( K + 1 \) time steps that are hereafter denoted by \( t^k = k \delta t \) for \( 0 \leq k \leq K \), where \( \delta t = T/K \). In the algorithm originally devised by Chorin and Temam, each time step is decomposed into two substeps as follows. For each time step, solve first

\[
\begin{aligned}
\frac{u^{k+1} - u^k}{\delta t} - \nabla^2 u^{k+1} &= f^{k+1} \\
u^{k+1} &= 0,
\end{aligned}
\]

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then project the provisional velocity $\tilde{u}^{k+1}$ onto $H$; in other words, solve

$$
\begin{align*}
\frac{\tilde{u}^{k+1} - u^k}{\delta t} + \nabla p^{k+1} &= 0 \\
\nabla \cdot \tilde{u}^{k+1} &= 0 \\
u^{k+1} \cdot n_{|\partial\Omega} &= 0.
\end{align*}
$$

(2.6)

The series $(u^k)$ is initialized by $u^0 = v_0$. The velocity $u^{k+1}$ is a prediction of $u(t^{k+1})$, and $\tilde{u}^{k+1}$ is a correction of $u^{k+1}$.

One possible improvement of the algorithm above consists in predicting a better value of the provisional velocity $u^{k+1}$ by putting the gradient of the pressure that has been calculated at the time step $t^k$ in the right-hand side of (2.5). This algorithm, hereafter referred to as the incremental form of the projection technique [11], consists in the following. Initialize the series $(u^k)$ and $(p^k)$ respectively by $u^0 = v_0$ and $p^0 = p|_{t=0}$, assuming that $p \in C^0(0, T; L^2(\Omega)/\mathbb{R})$. For each time step solve

$$
\begin{align*}
\frac{u^{k+1} - u^k}{\delta t} - \nabla^2 u^{k+1} &= f^{k+1} - \nabla p^k \\
\tilde{u}^{k+1} \cdot n_{|\partial\Omega} &= 0,
\end{align*}
$$

(2.7)

and project $\tilde{u}^{k+1}$ onto $H$

$$
\begin{align*}
\frac{\tilde{u}^{k+1} - u^k}{\delta t} + \nabla (p^{k+1} - p^k) &= 0 \\
\nabla \cdot \tilde{u}^{k+1} &= 0 \\
u^{k+1} \cdot n_{|\partial\Omega} &= 0.
\end{align*}
$$

(2.8)

Note that this algorithm assumes more regularity than the non incremental one since it requires an additional condition, i.e. $p^0 = p|_{t=0}$, that was not specified in the original Stokes problem (2.1) so that some regularity on $p$ as $t \to 0$ needs to be assured.

Step (2.6) and (2.8) are called projection steps since, according to theorem 2.1, they are equivalent to $u^{k+1} = P_H u^{k+1}$ and either

$$
\nabla p^{k+1} = (\tilde{u}^{k+1} - P_H \tilde{u}^{k+1})/\delta t \quad \text{or} \quad \nabla (p^{k+1} - p^k) = (u^{k+1} - P_H u^{k+1})/\delta t,
$$

where $P_H$ is the orthogonal projection of $L^2(\Omega)^d$ onto $H$. In both cases, the velocity $\tilde{u}^{k+1}$ is a prediction of $u(t^{k+1})$ that satisfies the correct boundary condition but is not divergence free. This defect is corrected by projecting $\tilde{u}^{k+1}$ onto $H$ (this step has given its name to the method). However, the end-of-step velocity, $u^{k+1}$, does not satisfy exactly the correct boundary condition since its tangential component is not necessarily zero.
Note that fractional step techniques (2.5)-(2.6) and (2.7)-(2.8) uncouple viscous diffusion and incompressibility. In practice, these techniques require solving Helmholtz problems and performing projections onto $H$, whereas classical coupled techniques usually involve a Uzawa operator $\nabla \cdot (I_d - \sigma \nabla^2)^{-1} \nabla$ where $\sigma$ is proportional to $\delta t$ and $I_d$ is the identity. This operator, called after Uzawa’s algorithm in which it is implicitly used (see for instance Temam [22, p 138]), is non-local and ill-conditioned as the time step tend to zero (see also § 7 for other details).

When it comes to analyzing the convergence of projection algorithms (2.5)-(2.6) and (2.7)-(2.8), it is sufficient to restrict the analysis to that of the incremental algorithm, for the error equations of the non-incremental one can be put into an incremental form as follows:

$$\begin{align*}
\frac{\tilde{e}^{k+1} - \tilde{e}^k}{\delta t} - \nabla^2 \tilde{e}^{k+1} &= R^{k+1} - \nabla p(t^{k+1}) \\
\tilde{e}^{k+1} &= 0,
\end{align*}$$

and

$$\begin{align*}
\frac{\tilde{e}^{k+1} - \tilde{e}^k}{\delta t} + \nabla (\delta^{k+1} - p(t^{k+1})) &= 0 \\
\nabla \cdot \tilde{e}^{k+1} &= 0 \\
\tilde{e}^{k+1} \cdot n_{|\partial \Omega} &= 0.
\end{align*}$$

Where $R^{k+1}$ is the integral Taylor residual, and we have defined the error functions $\tilde{e}^k = u(t^k) - u^k$, $\tilde{e}^k = u(t^k) - \bar{u}^k$ and $\delta^k = p(t^k) - p^k$. As a consequence, in the following we only consider the incremental form of the projection algorithm.

Global accuracy of projection schemes can be further improved by replacing the one-step backward Euler scheme in (2.7) by a Crank-Nicolson approximation as Van Kan did [25] or by a two-step backward Euler approximation. Stability and convergence of some of these modified scheme is studied in [13], [15], [16], [20], [21] and [25], but these considerations are out of the scope of the present paper. The objective of the work presented herein is to bring some answers to questions concerning spatially discrete approximations of the projection step (2.6) or (2.8).

### 2.3. The spatially discrete unsteady Stokes problem

Let $X_h$ and $M_h$ be convergent, internal, and stable approximations of $H^1(\Omega)^d$ and $L^2(\Omega)/\mathbb{R}$. It is hereafter assumed that $X_h$ and $M_h$ are finite...
dimensional vector spaces. We define $X'_h$ the dual of $X_h$; $X'_h$ is identical to $X_h$ in terms of vector space but is equipped with the dual norm induced by the scalar product of $L^2(\Omega)^d$. We identify $M_h$ with its dual space, for the natural norm of $M_h$ is that of $L^2(\Omega)$.

We now introduce the continuous bilinear form $b_h : X_h \times M_h \to \mathbb{R}$ so that $b_h(u_h, p_h) = - (\text{div } u_h, p_h)$, and we associate with $b_h$ the continuous linear operator $B_h : X_h \to M_h$ and its transpose $B_h^t : M_h \to X'_h$ so that for every couple $(u_h, p_h)$ in $X_h \times M_h$ we have $(B_h u_h, p_h) = b_h(u_h, p_h)$ and $(u_h, B_h^t p_h) = b_h(u_h, p_h)$. We assume that $B_h : X_h \to M_h$ is onto. An important consequence of the surjectivity of $B_h$ is summarized by the following well-known result which is a corollary of Banach's closed range theorem.

**Lemma 2.1**: Let $E$ and $F$ be two Hilbert spaces, and $T \in \mathcal{L}(E, F)$. The following propositions are equivalent:

(i) $T : E \to F$ is onto.

(ii) $T^t : F^* \to \ker (T)^0$ is one to one (3) and there is $\beta > 0$, so that $|T^t p|_{E^*} \geq \beta |p|_E$ for all $p \in E$.

For a proof, the reader is referred to Brezzi [5] or Girault-Raviart [10, pp. 58-59]. As a result, there is $\beta_h > 0$ so that

\[ \forall q_h \in M_h, \quad |B_h^t q_h|_{X'_h} \geq \beta_h |q_h|_0. \]

The constant $\beta_h$ is sometimes referred to as the inf-sup constant or the LBB constant (LBB being for Ladyzhenskaya-Babuška-Brezzi). A large choice of discrete spaces $X_h$ and $M_h$ satisfying such a condition is available in the literature. A review of compatible spaces in the framework of finite elements may be found in Girault-Raviart [10]. For spectral approximation see, for instance, Bernardi-Maday [4].

The null space of $B_h$ playing an important rôle in the following, we set $V_h = \ker (B_h)$, and we equip $V_h$ with the norm induced by that of $X_h$. We also define by $H_h = V_h$ in term of vector space and we equip $H_h$ with the norm of $L^2(\Omega)^d$ (in some sense $H_h$ plays the role of the completion of $V_h$ in $(L^2(\Omega)^d$).

Let us also introduce the continuous bilinear form $a_h : X_h \times X_h \to \mathbb{R}$ so that $a_h(u_h, v_h) = (\nabla u_h, \nabla v_h)$, and recall that, thanks to the Poincaré inequality in $H^1_0(\Omega)^d$, $a_h$ is $X_h$-elliptic; that is,

\[ \exists \alpha > 0, \forall u_h \in X_h, \quad a_h(u_h, u_h) \geq \alpha |u_h|^2. \]

We associate with $a_h$ the linear continuous operator $A_h : X_h \to X'_h$ so that for all $(u_h, v_h) \in X_h \times X$, $a_h(u, v) = (A_h u_h, v_h)$.

\[ (\mathbb{E}) \text{ Recall that the polar set of a space } V \subset E \text{ is defined by } V^0 = \{ e' \in E' ; \langle e', v \rangle = 0, \forall v \in V \}. \]
In the functional framework defined above, the spatially discrete version of the time-dependent Stokes problem can be formulated as follows. For \( f_h \in L^2(0, T, X_h) \) and \( v_{0,h} \in H_h \), find \( u_h \in L^2(0, T ; X_h) \cap C^0(0, T ; H_h) \) and \( p_h \in L^2(0, T ; M_h) \) so that

\[
\begin{align*}
\frac{du_h}{dt} + A_h u + B_h^t p &= f_h \\
B_h u_h &= 0 \\
u_{f=0} &= v_{0,h},
\end{align*}
\]

(2.11)

where \( f_h \) and \( v_h \) are suitable approximations of \( f \) and \( v_0 \) in \( X_h \). The data, \( f \) and \( v_0 \), are assumed to be as smooth as needed, and in the rest of the paper we focus on time approximations of (2.11). This problem has a unique solution \( (u_h, p_h) \), and this solution is stable (in the appropriate norms) with respect to the data.

Since \( X_h \) and \( M_h \) are convergent and stable internal approximations of \( H_0^1(\Omega)^d \) and \( L^2(\Omega)/\mathbb{R} \) respectively, the solution to (2.11) converges in an appropriate sense to that of the continuous unsteady Stokes problem (2.1). Our main concern now consists in approximating the time derivative in (2.11). In what follows, we are exclusively concerned with time approximations of problem (2.11) by means of projection techniques similar to (2.5)-(2.6) or (2.7)-(2.8).

3. A FULL DIRICHLET BOUNDARY CONDITION ON THE END-OF-STEP VELOCITY

3.1. The functional framework

In this section we build a discrete projection algorithm in which we take the provisional velocity \( \tilde{u}_h \) and the end-of-step velocity \( u_h \) in the same approximation space.

In order to build an analogy between the discrete framework and its continuum counterpart, we introduce a subspace of \( M_h \) that is the analogue of \( H_0^1(\Omega) \subset L^2(\Omega) \). For this purpose we define the positive bilinear form \( (p, q)_{M^1_h} = (B_h^t p, B_h^t q) \). According to (ii) in lemma 2.1, it is clear that \( (\cdot, \cdot)_{M_h^1} \) is a scalar product, and \( |p|_{M_h^1} = |B_h^t p|_0 \) is a norm. We now define \( M_h^1 \) so that \( M_h^1 = M_h \) in terms of vector space, but we equip \( M_h^1 \) with the norm \( |\cdot|_{M_h^1} \). Furthermore, we define \( Y_h = X_h \) in term of vector space and we equip \( Y_h \) with the norm of \( L^2(\Omega)^d \). The introduction \( M_h^1 \) and \( Y_h \) is justified by

**COROLLARY 3.1:** We have the stable, orthogonal decomposition:

\[
Y_h = H_h \oplus B_h^t(M_h^1).
\]

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Proof: Let \( l_h \in Y_h \) and define \( P_{H_h} : Y_h \rightarrow H_h \) the orthogonal projection onto \( H_h \). We have \((l_h - P_{H_h}l_h, v_h) = 0\) for all \( v_h \) in \( H_h \); in other words we also have \((l_h - P_{H_h}l_h, v_h) = 0\) for all \( v_h \) in \( V_h \); that is to say, \((l_h - P_{H_h}l_h) \in V_h^0\). From (ii) of lemma 2.1, we infer that there is a unique \( p_h \in M_h \) so that \( B'_h p_h = l_h - P_{H_h}l_h \). Furthermore, it is clear that \((P_{H_h}l_h, B'_h p_h) = 0\); as a result, \( |P_{H_h}l_h|^2 = (l_h, P_{H_h}l_h) \) and \( |B'_h p_h|^2 = (l_h, B'_h p_h) \), from which we infer that the decomposition is stable: \(|P_{H_h}l_h|_0 \leq |l_h|_0 \quad \text{and} \quad |p_h|_{M_h} \leq |l_h|_0\). \( \square \)

Note that the above decomposition of \( Y_h \) is the spatially discrete counterpart of the classical decomposition: \( L^2(\Omega) = H \oplus \nabla (H^1(\Omega) / \mathbb{R}) \).

### 3.2. The discrete projection algorithm

With the functional framework introduced above, the logical implementation of the viscous step (2.7) consists in looking for \( \tilde{u}^{k+1}_h \) in \( X_h \) so that

\[
\frac{\tilde{u}^{k+1}_h - u^k_h}{\delta t} + A_h \tilde{u}^{k+1}_h = f^{k+1}_h - B'_h p^k_h. \tag{3.2}
\]

This problem is well posed thanks to the \( X_h \)-ellipticity of \( A_h \). Note that \( \tilde{u}^{k+1}_h \), being approximated in \( X_h \), satisfies the Dirichlet condition \( \tilde{u}^{k+1}_h|_{\partial \Omega} = 0 \). We now turn the attention to the discrete projection step.

The projection step of the incremental algorithm can be implemented as follows. Find \( u^{k+1}_h \) in \( Y_h \) and \( p^{k+1}_h - p^k_h \) in \( M_h \) so that

\[
\begin{cases}
\frac{u^{k+1}_h - u^k_h}{\delta t} + B'_h(p^{k+1}_h - p^k_h) = 0 \\
B_h u^{k+1}_h = 0.
\end{cases} \tag{3.3}
\]

According to corollary 3.1 this problem is well posed. Actually, the couple \((u^{k+1}_h, \delta t(p^{k+1}_h - p^k_h))\) is the decomposition of \( \tilde{u}^{k+1}_h \) in \( H_h \oplus B'_h(M'_h) \); that is, \( \tilde{u}^{k+1}_h = P_{H_h}u^{k+1}_h \). Note, however, that this way of setting the discrete projection step may not seem the most appropriate since the velocity test functions...
involved satisfy a Dirichlet boundary condition. In order to emphasize this point we can reformulate (3.3) as follows: find \( u_h^{k+1} \) in \( X_h \) and \( p_h^{k+1} \) in \( M_h \) so that

\[
(3.4) \begin{cases}
\forall v_h \in X_h \subset H^1_0(\Omega)^d, \quad \frac{1}{\delta t} (u_h^{k+1} - \tilde{u}_h^{k+1}, v_h) - (\nabla \cdot v_h, p_h^{k+1} - p_h^k) = 0 \\
\forall q_h \in M_h \subset L^2(\Omega)/\mathbb{R}, \quad (\nabla \cdot u_h^{k+1}, q_h) = 0 .
\end{cases}
\]

\( X_h \) being an internal approximation to \( H^1_0(\Omega)^d \), \( u_h^{k+1} \) satisfies \( u_h^{k+1} \rvert_{\partial \Omega} = 0 \) and the velocity test functions satisfy \( v_h \rvert_{\partial \Omega} = 0 \), whereas it might seem more appropriate to enforce only \( u_h^{k+1} \cdot n \rvert_{\partial \Omega} = 0 \) and \( v_h \cdot n \rvert_{\partial \Omega} = 0 \) as suggested by the continuous projection step (2.6) or (2.8). We show in the following that this choice has some consequence on the condition number of the pressure operator involved in the linear system (3.4).

### 3.3. The condition number issue

If the velocity \( u_h^{k+1} \) is eliminated from (3.3), the projection step reduces to solving the following pressure problem

\[
(3.5) \quad B_h B_h^t(p_h^{k+1} - p_h^k) = \frac{B_h u_h^{k+1}}{\delta t} .
\]

We now turn the attention to the influence of the end-of-step boundary condition on the condition number of the pressure operator \( B_h B_h^t \). We analyze this influence for finite element approximations and for spectral approximations. It is shown that the full Dirichlet boundary condition on the end-of-step velocity is optimal, in term of condition number of \( B_h B_h^t \) for finite element approximations, whereas it is not for spectral approximations.

In the following we assume that \( X_h \) and \( M_h \) are composed of finite elements based on a uniformly regular triangulation \( \mathcal{T}_h \) of \( \Omega \), the characteristic mesh size of which is denoted by \( h \). We also assume that these two spaces are uniformly compatible in the sense that the inf-sup constant \( \beta_h \) is independent of \( h \). Recall that for uniformly regular triangulation we have the inverse inequality.

**LEMMA 3.1:** (cf. Girault-Raviart [10, p. 103]). There is a constant \( c > 0 \) independent of \( h \) so that

\[
(3.6) \quad \forall v_h \in X, \quad |\nabla v_h|_0 \leq ch^{-1} |v_h|_0 .
\]

We now give an upper bound on the condition number \( \kappa(B_h B_h^t) \).
THEOREM 3.1: There is a constant $c > 0$ so that

$$\kappa(B_h B'_h) \leq \frac{c}{\beta_h^4 h^2}. \quad (3.7)$$

Proof: Let $p_h$ be in $M_h$ and define $g_h$ in $M_h$ so that $g_h = B_h B'_h p_h$. By setting $u_h = -B'_h p_h$ we have

$$\begin{cases}
  u_h + B'_h p_h = 0 \\
  B_h u_h = g_h.
\end{cases}$$

(a) From this system we deduce the bound $|u_h|_0^2 = -(B_h u_h, p_h) \leq |g_h|_0 |p_h|_0$. Furthermore, (ii) in lemma 2.1 yields $|u_h|_0 = |B'_h p_h|_0 \geq \beta_h |p_h|_0$. As a result, we have $\beta_h^2 |p_h|_0 \leq |g_h|_0^2$, from which we deduce that the smallest eigenvalue of $B_h B'_h$ is bounded from below by $\beta_h^2$.

(b) From the system above we also deduce $|u_h|_0^2 = (\text{div} u_h, p_h)$, which together with the inverse inequality (3.6), yields $h |u_h|_0 \leq c |p_h|_0$. Furthermore, we have $|g_h|_0^2 = -(\text{div} u_h, g_h)$, which for the same reason as above yields $h |g_h|_0 \leq c |u_h|_0$. By combining the two bounds above, we obtain that the largest eigenvalue of $B_h B'_h$ is bounded from above by $c h^2$.

(c) The operator $B_h B'_h$ being symmetric, its condition number is equal to the ratio of its largest to its smallest eigenvalues. □

This bound on $\kappa(B_h B'_h)$ is likely to be optimal since the underlying partial differential equation is a Poisson problem supplemented with a Neumann boundary condition, and it is known that approximating such a problem by finite elements yields an operator the condition number of which is equivalent to $1/h^2$. Hence, the important conclusion of this section is that although approximating the projection step by means of test functions satisfying $v_h|_{\partial \Omega} = 0$ does not seem natural, it nevertheless remains optimal in the framework of finite element approximations since it yields a pressure operator with an optimal condition number.

Now assume that $\Omega = \mathbb{R}^d$, and let $N \geq K > 0$ be two integers. Let $X_h = P_N(\Omega) \cap H^1(\Omega)^d$ be the space of the polynomial velocities on $\Omega$ vanishing on $\partial \Omega$ and the partial degree of which are less than or equal to $N$. Likewise, we define $M_h = P_K(\Omega) \cap L^2(\Omega) \mathbb{R}^d$ the space of the pressures on $\Omega$ that are polynomials with partial degree less than or equal to $K$. We assume that $M_h$ is compatible with $X_h$, and we denote by $\beta_{NK}$ the corresponding inf-sup constant (cf. Bernardi-Maday [4] for a review on such approximations). The counterpart of lemma 2.1 for spectral approximations is the following.
Lemma 3.2: (cf. Canuto-Quarteroni [7] lemma 2.1, p. 73). There is a constant \( c > 0 \), independent of \( N \), so that
\[
\forall v_n \in P_N([-1, +1]), \quad |\nabla v_n|_0 \leq cN^2|v_n|_0.
\]

We now give an upper bound on the condition number of the pressure operator.

Theorem 3.2: There is \( c > 0 \) so that
\[
\kappa(B_h B_h') \leq \frac{cN^4}{\beta_{NK}^2}.
\]

Proof: Proceed as for the proof of theorem 3.1 \( \square \)

In general the exponent 4 is optimal for spectral Poisson problems supplemented with either Dirichlet or Neumann boundary conditions. It may be further reduced to 3 through the action of a mass matrix if the base functions are conveniently weighted (cf. Bernardi-Maday [4, Lemma 5.5, ch. III]). Note that the present functional framework is intrinsic (i.e. no particular base is chosen); that is, we deal with operators instead of matrices. In this context, the intrinsic counterpart of the mass matrix is the identity operator. This reason explains why we obtained the exponent 4 instead of 3.

The bound (3.9) would be optimal if \( \beta_{NK} \) were bounded from below by a constant when \( N \) and \( K \) tend to infinity. Unfortunately, in general \( \beta_{NK} \) tends to zero. For instance, for \( K = N - 2 \) (i.e. the \( P_{N-2}^0, P_N \) approximation) we have (see Bernardi-Maday [4, p. 147])
\[
\kappa(B_h B_h') \leq \frac{c}{\sqrt{N}} \leq \frac{c'}{\sqrt{N}}.
\]

As a result, \( \kappa(B_h B_h') \leq cN^5 \) which is no longer optimal. This default to the optimality is even worse if the pressure is taken in \( P_N(\Omega) \), for in this case (once the spurious modes are discarded) the inf-sup constant behaves like \( 1/N \).

In conclusion, enforcing \( v|_{\partial\Omega} = 0 \) on the test functions for the projection step may not be optimal in the framework of spectral approximations. This default to the optimality comes from the inf-sup constant that vanish as the number of modes increases. It is shown in the next section that if the boundary condition on the velocity test functions is relaxed (i.e. \( v \cdot n|_{\partial\Omega} = 0 \)), then the corresponding inf-sup constant can be uniformly bounded from below by a strictly positive constant.

4. THE NORMAL TRACE OF THE END-OF-STEP VELOCITY ENFORCED

4.1. The functional framework

In order to take into account the boundary condition \( v \cdot n|_{\partial\Omega} = 0 \), we introduce \( H_0^{\text{div}}(\Omega) = \{ v \in L^2(\Omega)^d, \ \text{div} \ v \in L^2(\Omega), \ v \cdot n|_{\partial\Omega} = 0 \} \). Equipped
with the norm \((|v|^2 + |\text{div} v|^2)^{1/2}\), \(H_0^\text{div} (\Omega)\) is a Hilbert space, and we have 
\[ H_0^\text{div} (\Omega)^d \subset H_0^\text{div} (\Omega) \subset L^2(\Omega)^d \subset H_0^\text{div} (\Omega)' \subset H^{-1}(\Omega)^d, \]
where the embeddings are dense and continuous.

Let \(Y_h\) be a finite dimensional, internal and convergent approximation of \(H_0^\text{div} (\Omega)\). Though it may seem natural to equip \(Y_h\) with the norm of \(L^2(\Omega)^d\), we equip it with the norm of \(L^2(\Omega)\) for it will be sufficient for our purposes as shown below. A discrete divergence operator \(C_h : Y_h \rightarrow M_h = M^1_h\) and its transpose \(C_h^t : M_h \rightarrow Y_h^t\) are defined so that for all \((v_h, q_h)\) in \(Y_h \times M_h\) we have 
\[ (C_h v_h, q_h) = - (\text{div} v_h, p_h) = (v_h, C_h^t p_h). \]
We assume also that \(C_h : Y_h \rightarrow M_h\) is onto in the sense that it satisfies the following inf-sup condition
\[ \exists \beta_h > 0, \forall q_h \in M_h, \quad |C_h^t q_h|_0 \geq \beta_h |q_h|_0. \]

Now, in order to build some discrete counterpart to \(H^1(\Omega)\), define 
\[ H_h^1 = \ker (C_h) \quad \text{and} \quad H_h^0 = \ker (C_h^t). \]

COROLLARY 4.1: We have the decomposition :
\[ Y_h = H_h^1 \oplus C_h^t(M^1_h). \]

This decomposition is orthogonal and stable with respect to the \(L^2\) norm.

It is also assumed that \(X_h \subset Y_h\). We denote by \(i_h : X_h \rightarrow Y_h\) the natural injection of \(X_h\) into \(Y_h\) and \(i_h^t : Y_h^t \equiv Y_h' \rightarrow X_h^0\) its transpose. Note that \(i_h^t\) can be identified to the \(L^2\) projection of \(Y_h^t\) onto \(X_h\); in particular, we have
\[ |i_h^t v_h|_0 \leq |v_h|_0. \]

The relationship between \(B_h\) and \(C_h\) is brought to light by

PROPOSITION 4.1: \(C_h\) is an extension of \(B_h\) and \(i_h^t C_h = B_h^t\).

Proof: (a) For all \((v_h, q_h)\) in \(X_h \times M_h\), we have 
\[ (C_h i_h v_h, q_h) = - (\text{div} v_h, q_h) = (B_h v_h, q_h) \]
since \(X_h \subset Y_h\); that is to say, \(C_h i_h v_h = B_h v_h\) for all \(v_h \in X_h\).

(b) From (a) we have \(C_h i_h = B_h\), from which we easily infer 
\[ i_h^t C_h = B_h^t. \]

4.2. The discrete projection algorithm

In the framework defined above the viscous step reads as follows:

\[ \frac{\hat{u}_h^{k+1} - i_h^t u_h^k}{\delta t} + A_h \hat{u}_h^{k+1} = f_h^{k+1} - B_h p_h^k. \]
This problem is well posed thanks to the ellipticity of $A_h$. Note that $u_h^k$ must be projected onto $X'_h$ since it naturally belongs to $Y_h$.

The discrete projection step reads: find $u_{h}^{k+1}$ in $Y_h$ and $p_{h}^{k+1}$ in $M_h$ so that

$$
\begin{align*}
\frac{u_{h}^{k+1} - i_h u_{h}^{k}}{\delta t} + C'_h (p_{h}^{k+1} - p_{h}^{k}) &= 0 \\
C_h u_{h}^{k+1} &= 0.
\end{align*}
$$

Corollary 4.1 implies that this linear system has a unique solution.

Note that the solvability of the viscous and projection steps (4.4)-(4.5) do not require $B'_h$ to be into. In other words, the pressure is uniquely defined (in a seemingly stable manner) by the projection step (4.5). At this point it may come to one’s mind that requiring $B'_h$ to be onto is an unnecessary stringent condition. As a result, one may think of choosing $X_h$ and $M_h$ with no reference to any inf-sup condition so that $B'_h$ may possibly have spurious modes. However, when it comes to studying the convergence in time of the global scheme, it is shown below (see proof of theorem 6.2) that the discrete pressure of interest is that which is rid of the possible spurious modes of $B'_h$, and the global stability constant on the pressure is not that of $C'_h : M_h \rightarrow Y_h$ but that of $B'_h : M_h \rightarrow X'_h$.

In order to illustrate the definitions above, let us give an example in the framework of spectral approximations (this example is borrowed from Azaiez-Bernardi-Grundmann [1]). Define $\Omega = ] - 1, + 1[$, and let $X_h = \mathbb{P}_N(\Omega) \cap H^1_0(\Omega)^d$ be the space of the polynomial velocities on $\Omega$ vanishing on $\partial \Omega$ and the partial degree of which are less than or equal to $N$. Likewise, define $Y_h = \mathbb{P}_N(\Omega) \cap H^\text{div}_0(\Omega)$ the space of the velocities which are polynomials with partial degree less than or equal to $N$ and the normal component of which vanish on $\partial \Omega$. When the pressure space is $P_N(\Omega)/\mathbb{R}$ and the velocity space is $Y_h$, it can be shown that the gradient operator has three spurious pressure modes (cf. [1, Lemma 4.1]):

$$\text{span} (L_N(x), L_N(y), L_N(x) L_N(y)),$$

where $L_N$ is the Legendre polynomial of order $N$. We get rid of these unwelcome modes by defining $N_h$ as the orthogonal of the modes in question in $P_N(\Omega)/\mathbb{R}$. Thus defined, $N_h$ and $Y_h$ are compatible and there is an inf-sup constant, $\beta'$, independent of $N$ and strictly positive (cf. [1, Lemma 4.2]) so that

$$\inf \sup_{g_h \in N_h, u_h \in Y_h} \frac{(\text{div } u_h, g_h)}{|u_h|_0 |g_h|_0} \geq \beta'.$$

In this spectral framework, the condition number of the pressure operator $C_h C'_h$ satisfies the optimal bound

$$\kappa(C_h C'_h) \leq cN^4.$$
Furthermore, it is shown in Bernardi-Maday [4, Proposition 5.2, p. 135] that the discrete gradient $B'_h : N_h \to X'_h$ has still four spurious modes:

$$S_h = \text{span} \{ L'_N(x), L'_N(y), L'_N(x) y L'_N(y), xL'_N(x) L'_N(y), xL'_N(x) y L'_N(y)\}.$$

This unwelcome modes should be discarded by defining $M'_h$ as the orthogonal of $S'_h$ in $N'_h$. Hence, not only the pressure space should be rid of the three modes span $\{ L_N(x), L_N(y), L_N(x) L_N(y)\}$ so that $C'_h$ is into, but it should also be rid of the four spurious modes of $S_h$. In practice, the regularization of the pressure can be done as a post processing. Furthermore, it can be shown (cf. [4, p. 135]) that the resulting stability constant of $B'_h$, $B'_h$, is equivalent to $\nu N$.

In conclusion, introducing velocity test functions satisfying the boundary condition $v \cdot n_{|\partial \Omega} = 0$ may be justified for some spectral approximations, for it yields a pressure operator with an optimal condition number. Note, however, that this procedure is less economical than the previous one since it involves two approximation spaces for the velocity and it involves two gradient operators (i.e. two matrices), namely $B'_h$ and $C'_h$. It is not clear whether the present approach should be preferred to the previous one as far as finite element approximations are concerned (see also Quartapelle [19, pp. 191-201] for other details on this technique). Furthermore, although the algorithm (4.4)-(4.5) does not explicitly require $B'_h$ to be into, the pressure of interest (i.e. the one on which we have some stability) is that which is rid of the spurious modes of $B'_h$ (if such modes exist).

5. THE PROJECTION STEP AS A POISSON PROBLEM

5.1. Motivation

Assume as in the previous sections that the projection step is formulated in the form of a Darcy problem with velocity test functions satisfying either a Dirichlet condition or a boundary condition only for the normal component. In practical implementations we have to choose particular bases of $X_h$ (or $Y_h$) and $M_h$. Each of these choices yields a mass matrix $\mathfrak{M}_h$ and a matrix $\mathfrak{B}_h$ associated with the divergence operator $B'_h$. For a velocity field $u_h$ in $X_h$ (or $Y_h$) and a pressure field $p_h$ in $M_h$, we denote by $U_h$ and $P_h$ the vectors of the components of $u_h$ and $p_h$ in the bases in question. In this context, the projection step (3.3) (or (4.5)) yields the following linear system in terms of the pressure unknowns

$$\mathfrak{B}_h \mathfrak{M}_h^{-1} \mathfrak{B}_h (P_{k+1} - P_k) = \frac{\mathfrak{B}_h \tilde{U}_{k+1}}{\delta t}.$$

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Though this approach is quite natural, for it is based on the definition of the projection operator (cf. theorem 2.1), the presence of the inverse of the mass matrix may hamper its practicability in some circumstances. For instance, for finite element approximations the mass matrix is not diagonal, and the direct solution of the pressure problem may not be feasible, especially when a large number of unknowns is involved. In practice, alternative approaches consist in lumping the mass matrix (cf. Gresho and Chan [12, part II] or Quartapelle [19, pp. 191-201]). Though this technique may work, no stability result has yet been proven.

It is the purpose of this section to show that the mass matrix problem may be circumvented if the projection step is recast in the form of a Poisson problem (1.2), as advocated in Temam [24].

5.2. The functional framework

As in the previous sections we denote by $X_h$ the Hilbert space in which the provisional velocities are approximated. Recall that $X_h$ is an internal approximation of $H^1_0(\Omega)^d$. Thanks to the Poincaré-Wirtinger inequality in $H^1(\Omega)/\mathbb{R}$, we equip $H^1(\Omega)/\mathbb{R}$ with the equivalent norm $|\nabla p|_0$. We now introduce $M_h^1$, a stable and internal approximation of $H^1(\Omega)/\mathbb{R}$ and we equip it with the norm of $H^1(\Omega)/\mathbb{R}$ defined above. To make a clear difference between the $H^1$ norm in $M_h^1$, the $L^2$ norm, and the dual norm, we introduce $M_h$ and $M_h^{1'}$. These spaces are identical to $M_h^1$ in terms of vector space and they are respectively equipped with the $L^2$ norm and the dual norm induced by the $L^2$ scalar product.

Note that we now impose $M_h \subset H^1(\Omega)/\mathbb{R}$, whereas in the previous sections we only needed $M_h \subset L^2(\Omega)/\mathbb{R}$. In the following, the definitions of $A_h : X_h \rightarrow X_h'$, and $B_h : X_h \rightarrow M_h$ remain unchanged.

In order to build a discrete Poisson problem for the pressure, we introduce the continuous bilinear form $d_h : M_h^1 \times M_h^1 \rightarrow \mathbb{R}$ so that

$$
\forall (p_h, q_h) \in M_h^1 \times M_h^1, \quad d_h(p_h, q) = (\nabla p_h, \nabla q_h).
$$

This bilinear form is obviously $M_h^1$-elliptic. We associate with $d_h$ the linear continuous operator $D_h : M_h^1 \rightarrow M_h^{1'}$ so that $d_h(p_h, q) = (D_h p_h, q_h)$ for all $(p_h, q_h) \in M_h^1 \times M_h^1$. The ellipticity of $d_h$ implies that $D_h : M_h^1 \rightarrow M_h^{1'}$ is one to one.
We introduce also the vector space $Y_h = X_h + \nabla M_h^l$ and we equip it with the norm of $L^2(\Omega)^d$. It is clear that $X_h \subset Y_h$. We respectively denote by $i_h$ $X_h \to Y_h$ and by $i_h'$ $Y_h' \to X_h'$ the natural injection of $X_h$ into $Y_h$ and its transpose. Note that we have the following stability inequality

\[ \forall v_h \in Y_h, \quad |i_h' v_h|_0 \leq |v_h|_0 \]

5.3. The discrete projection algorithm

In a way much similar to that in the other sections, the viscous step reduces to finding $u_h^{k+1}$ in $X_h$ so that

\[ \frac{u_h^{k+1} - i_h' u_h^k}{\delta t} + A_h u_h^{k+1} = f_h^{k+1} - B_h' p_h^k \]

The ellipticity of $A_h$ guarantees that this problem is well posed. Note that for reasons explained further, $u_h^k$ must be projected onto $X_h'$ for $u_h^k$ naturally belongs to $Y_h = X_h + \nabla M_h^l$ (see (5.6)).

We now solve the projection step (2.8) as a Poisson problem supplemented with a homogeneous Neumann condition

\[ D_h(p_h^{k+1} - p_h^k) = \frac{B_h u_h^{k+1}}{\delta t} \]

Given the ellipticity of $D_h$, this discrete problem has a unique solution. Note that this problem is very classical, and the CFD and applied mathematics communities have spent a lot of energy devising efficient numerical algorithms permitting to solve it. In some sense this problem is more attractive than its div-grad counterparts (3.3) or (4.5) since its matrix formulation does not involve the inverse of the mass matrix.

The last step of the algorithm consists in correcting the velocity. This is done by setting

\[ u_h^{k+1} = u_h^{k+1} - \delta t \nabla (p_h^{k+1} - p_h^k) \]

Note that $u_h^{k+1}$ belongs to $X_h + \nabla M_h^l$ which is a subset of $L^2(\Omega)^d$. Strictly speaking, this velocity is not divergence free since there is no reason for $\text{div } \tilde{u}^{k+1}$ to be equal to $\nabla^2 (p_h^{k+1} - p_h^k)$. For instance, if $P_1$ finite elements are used for approximating the pressure, the Laplacian of the pressure increment is a $H^{-1}(\Omega)$ measure, whereas the divergence of the provisional velocity is in $L^2(\Omega)$, hence, the divergence of $u_h^{k+1}$ is a $H^{-1}(\Omega)$ measure. However, we have
Proposition 5.1: \( u_h^{k+1} \) is weakly divergence free in the sense that

\[
\forall q_h \in M_h, \quad (u_h^{k+1}, \nabla q_h) = 0,
\]

and its divergence and normal trace converge to zero (in some weak sense) when \( h \to 0 \) if \( u_h^{k+1} \) converges in \( H_0^1(\Omega)^d \) when \( h \to 0 \).

Proof: (a) By definition, (5.5) is equivalent to

\[
\forall q_h \in M_h, \quad \delta t(\nabla(p_h^{k+1} - p_h^k), \nabla q_h) + (\mathrm{div} \; \bar{u}_h^{k+1}, q_h) = 0.
\]

Furthermore, by taking the inner product of (5.6) by \( \nabla q_h \) we obtain

\[
\forall q \in M_h, \quad (u_h^{k+1}, \nabla q_h) = - (\mathrm{div} \; \bar{u}_h^{k+1}, q_h) - \delta t(\nabla(p_h^{k+1} - p_h^k), \nabla q_h),
\]

from which (5.7) is easily deduced.

(b) Assume for sake of simplicity that \( \Omega \) is a convex polygon and \( \bar{u}_h^{k+1} \) converges in \( H_0^1(\Omega)^d \) to some function \( \bar{u} \), then the series of functions \( (p_h^{k+1} - p_h^k) \) converges in \( H^1(\Omega)/\mathbb{R} \) to the solution of the Poisson problem \( \nabla^2 \phi = \mathrm{div} \; \bar{u} / \delta t \) and \( \partial \phi / \partial n \mid_{\partial \Omega} = 0 \). As a result, \( u_h^{k+1} \) converges to \( u = \bar{u} - \delta t \nabla \phi \) in \( L^2(\Omega)^d \); the limit function \( u \) is divergence free and its normal trace is zero. □

Indeed, the scheme (5.4)-(5.5) can be put formally in a form quite similar to that of the two other techniques described in the sections above. A discrete divergence operator \( C_h : Y_h \to M_h \) can be defined by

\[
(5.8) \quad \forall v_h \in Y_h, \; \forall q_h \in M_h, \quad (C_h v_h, q_h) = (v_h, \nabla q_h).
\]

By setting \( H_h = \ker(C_h) \), we clearly have

\[
(5.9) \quad Y_h = H_h \oplus C_h^\prime(M_h^\prime).
\]

Furthermore, the relation between \( C_h \) and \( B_h \) is brought to light by

Proposition 5.2: \( C_h \) is an extension of \( B_h \) and \( i_h^\prime C_h^\prime = B_h^\prime \).

The particular choice we have made on \( Y_h \) implies that

Proposition 5.3: \( C_h^\prime \) is the restriction of \( \nabla \) to \( M_h \).

Proof: For all \( (v_h, q_h) \) in \( Y_h \times M_h \), we have \( (C_h^\prime q_h, v_h) = (\nabla q_h, v_h) \); that is to say \( (C_h^\prime q_h - \nabla q_h, v_h) = 0 \). But \( \nabla q_h \) is in \( Y_h \) by definition and \( C_h^\prime q \) is in \( Y_h^\prime \) (\( = Y_h \) in terms of vector space), hence \( C_h^\prime q_h = \nabla q_h \). □
Corollary 5.1: The projection step (5.4)-(5.5) is equivalent to the problem: look for \( u_h^{k+1} \) in \( Y_h \) and \( p_h^{k+1} \) in \( M_h \) so that

\[
\begin{cases}
\frac{u_h^{k+1} - i_h u_h^{k+1}}{\delta t} + C_h^i (p_h^{k+1} - p_h^k) = 0 \\
C_h u_h^{k+1} = 0 .
\end{cases}
\]

Remark that the algorithm described above does not explicitly involve any compatibility condition between \( X_h \) and \( M_h \); that is, no inf-sup condition is required to ensure wellposedness of any of the fractional steps (5.4), (5.5), or (5.6). For instance, \((P_1, P_1)\) finite elements would be perfectly suited to the algorithm above. Actually a compatibility condition shows up when we are interested in the stability and the convergence of the scheme (see proof of theorem 6.2). After all, we are interested in approximating the velocity and pressure which are solution to (2.11), but uniqueness and stability on the pressure in (2.11) is ensured only if \( B_h^* \) has no spurious modes. Hence, if such modes exist, they have eventually to be discarded. If for some reason one is interested in solving the problem by means of continuous finite elements of degree one, a possible choice consists in using \((P_1 - iso-P_2, P_1)\) finite elements (cf. Bercovier-Pironneau [3]).

6. GENERALIZATION AND ERROR BOUNDS

6.1. Generalization

We show in this section that the three projection algorithms described above can be put into a unified framework.

The definitions of the spaces \( X_h \) and \( M_h \) together with that of the operators \( A_h \) and \( B_h \) are unchanged. We define \( Y_h \) a finite dimensional subspace of \( L^2(\Omega)^d \) and endow \( Y_h \) with the norm of \( L^2(\Omega)^d \); we assume also that \( X_h \subset Y_h \) (in terms of vector space) and we denote by \( i_h \) the continuous injection of \( X_h \) into \( Y_h \); the transpose of \( i_h \) is the \( L^2 \) projection of \( Y_h \) onto \( X_h \). Note that \( Y_h \) is an internal approximation of \( L^2(\Omega)^d \), for \( X_h \) is an approximation of \( H^1_0(\Omega)^d \) and \( H^1_0(\Omega)^d \) is dense in \( L^2(\Omega)^d \). In addition, we assume that there is an operator \( C_h : Y_h \rightarrow M_h \) so that \( C_h \) is an extension of \( B_h \); in other words we assume that we have the following commutative diagrams:

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Since $B_h$ is onto and $C_h$ is an extension of $B_h$, $C_h$ is necessarily onto. One consequence of this (together with (ii) of lemma 2.1) is that $|C_h q|_0$ is a norm; this norm is hereafter denoted by $|q|_{M_1} = |C_h q|_0$ and we denote by $M_1$ the vector space $M_h$ equipped with this norm. The null space of $C_h$ is denoted by $H_h$. The definitions above enable us to build a discrete counterpart of the aforementioned orthogonal decomposition $L^2(\Omega)^d = H \oplus \nabla (H^1(\Omega))$:

$$Y_h = H_h \oplus C_h(M_1).$$

The three algorithms described above can be put into the following unified form. The diffusion step reads: find $\tilde{u}_h \in X$ so that

$$\frac{\tilde{u}_h^{k+1} - i_h u_h^k}{\delta t} + A_h \tilde{u}_h^{k+1} = f_h^{k+1} - B_h p_h^k.$$  

The projection step consists in looking for $u_h^{k+1}$ in $Y_h$ and $p_h^{k+1}$ in $M_h$ so that

$$\begin{cases} 
\frac{u_h^{k+1} - i_h u_h^k}{\delta t} + C_h(p_h^{k+1} - p_h^k) = 0 \\
C_h u_h^{k+1} = 0.
\end{cases}$$

The decomposition (6.1) implies that this linear system has a unique solution. This step is a projection step in the sense that $u_h^{k+1}$ is the projection of $\tilde{u}_h^{k+1}$ onto $H_h$.

We now turn our attention to the convergence issue.

6.2. The convergence issue

We prove in this section that the solution to the projection algorithm composed of the viscous step (6.2) and the projection step (6.3) converges in some sense to the solution of (2.1). However, since a complete proof of
convergence is out of the scope of the present paper we only give the main ideas. For complete proofs of convergence in the context of the non-linear Navier-Stokes equations, the reader is referred to Guermond-Quartapelle [16].

For sake of simplicity, we shall compare the solution of the projection scheme (6.2)-(6.3) to that of the following coupled scheme set \( \omega^0 = v^0_h \) and for \( k \geq 0 \) solve

\[
\begin{align*}
\frac{w^{k+1}_h - w^k_h}{\delta t} + A_h w^{k+1}_h + B'_h q^{k+1}_h &= f^{k+1}_h, \\
B_h w^{k+1}_h &= 0
\end{align*}
\]

We shall assume that for some \( k_0 \) large enough, the solution to this algorithm satisfies the following local in time convergence result

\[
\max_{k_0 \leq k \leq K} \left[ |u(t^k) - w^k_h|_1 + |p(t^k) - q^k_h|_0 \right] \leq c(\delta t + h),
\]

where \( c \) is a generic constant that does not depend on \( h \) but possibly depends on the regularity of the data of (2.1). We will restrict our analysis to \( t^k \geq t^{k_0} \) in order to avoid a possible blow up of the error estimates at \( t = 0 \) due to a possible lack of smoothness of the solution to (2.1) (and/or incompatibility of the data at \( t = 0 \) [20]). We assume also that the extended gradient operator, \( C'_{h} \), is somewhat stable in \( H^1(\Omega) \) (a precise meaning of this stability is given in Guermond-Quartapelle [16]) so that we have

\[
\max_{k_0 \leq k \leq K} |C'_{h}(q^{k+1}_h - q^k_h)|_0 \leq c\delta t,
\]

Of course (6.5) and (6.6) can be proved under reasonable hypotheses on \( X_h \) and \( M_h \) and on the data of (2.1), the reader is referred to Guermond-Quartapelle [16] for further details.

In order to initialize our fractional step technique, we assume that we have carried out \( k_0 \) steps of (6.4), that is to say, we set \( u^{k_0}_h = w^{k_0}_h \) and \( p^{k_0}_h = q^{k_0}_h \) and the projection algorithm (6.2)-(6.3) is implemented for \( k \geq k_0 \).

Let us denote by \( e^k_h = w^k_h - u^k_h \), \( \tilde{e}^k_h = w^k_h - \tilde{u}^k_h \), and \( \epsilon^k_h = q^k_h - p^k_h \) the error functions. For conciseness we introduce the notation \( \delta z^{k+1} = z^{k+1} - z^k \) for any function \( z \). The ability of the solution to (6.2)-(6.3) to approximate that of (2.1) for \( k_0 \leq k \leq K \) is stated in

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THEOREM 6.1: If $\delta t$ is small enough, the solution to the projection scheme (6.2)-(6.3) satisfies:

$$
\max_{k_0 \leq i \leq k} \left| u(t^k) - u^k_h \right|_0 + \left[ \delta t \sum_{k=k_0}^{K} \left| u(t^k) - \tilde{u}^k_h \right|_1^2 \right]^{1/2} \leq c(\delta t + h).
$$

Proof: (a) By subtracting (6.2) from the first equation of (6.4), we derive the equation which controls the error $\tilde{e}^k_{h+1}$

$$
\frac{\tilde{e}^k_{h+1} - i^t_{h+1}e^k_{h+1}}{\delta t} + A_h e^k_{h+1} + B_h \psi_h^k = 0
$$

where we have set

$$
\psi_h^k = q_h^{k+1} - p_h^k = \delta t q_h^{k+1} + e_j^k.
$$

Note that we have used $i^t_{h+1}w_h^k = w_h^k$ since $w_h^k$ is in $X_h$.

Furthermore, noticing that $w_h^{k+1}$ is in $X_h$, $B_h w_h^{k+1} = 0$, and $C_h$ is an extension of $B_h$, we obtain the system of equations which controls $e_h^k$ and $e^{k+1}_h$

$$
\begin{cases}
\frac{e^{k+1}_h - i^t_h e^{k+1}_h}{\delta t} + C_h^t(e^{k+1}_h - \psi_h^k) = 0, \\
C_h e^{k+1}_h = 0. \\
\end{cases}
$$

(b) In order to obtain a bound on $e^{k+1}_h$, we take the inner product of (6.8) by $2 \delta t \tilde{e}^k_{h+1}$. Using the ellipticity of $A_h$ (the ellipticity constant is denoted by $\alpha$) together with the classical relation

$$
2(a, a - b) = |a|^2 + |a - b|^2 - |b|^2
$$

we obtain:

$$
|\tilde{e}^{k+1}_h|_0^2 + |\tilde{e}^{k+1}_h - i^t_h e^{k+1}_h|_0^2 + 2 \alpha \delta t |\tilde{e}^{k+1}_h|_1^2 + 2 \delta t(\tilde{e}^{k+1}_h, B_h^t \psi_h^k) = |i^t_h e^{k+1}_h|_0^2.
$$

The stability of $i^t_h$ yields

$$
|\tilde{e}^{k+1}_h|_0^2 + 2 \alpha \delta t |\tilde{e}^{k+1}_h|_1^2 + 2 \delta t(\tilde{e}^{k+1}_h, B_h \psi_h^k) \leq |e^{k+1}_h|_0^2.
$$

(c) In order to obtain some control on $B_h^t e^{k+1}_h$, we take the inner product of the first equation of (6.9) by $2 \delta t^2 C_h^t \psi_h^k$, and using the fact that $C_h$ is an extension of $B_h$ we obtain

$$
-2 \delta t(\tilde{e}^{k+1}_h, B_h^t \psi_h^k) + \delta t^2 |C_h^t e^{k+1}_h|_0^2 - |e^{k+1}_h - i^t_h e^{k+1}_h|_0^2 = \delta t^2 |C_h^t \psi_h^k|_0^2.
$$
With the help of (6.6), the right hand side of this equation is bounded from above as follows.

\[ \delta t^2 | C_h' \psi'_{h|0} |^2 = \delta t^2 | C_{h|0}^{r} (\delta_t q_{h|0}^{k+1} + e_{h|0}^{k+1}) |^2, \]

\[ \leq \delta t^2 (1 + \delta t) | C_{h|0}^{r} e_{h|0}^{k+1} |^2 + \delta t (1 + \delta t) | C_h' \delta_t q_{h|0}^{k+1} |^2, \]

\[ \leq \delta t^2 (1 + \delta t) | C_{h|0}^{r} e_{h|0}^{k+1} |^2 + c\delta t^3, \]

that is to say

\[ (6.11) \quad -2 \delta t (\varepsilon_{h|0}^{k+1}, B_h' \psi_{h|0}^{k+1}) + \delta t^2 | C_{h|0}^{r} e_{h|0}^{k+1} |^2 - | e_{h|0}^{k+1} - i_h^{k+1} |^2 \leq \delta t^2 (1 + \delta t) | C_{h|0}^{r} e_{h|0}^{k+1} |^2 + c\delta t^3. \]

(d) We obtain some control on \( e_{h|0}^{k+1} \) by taking the inner product of (6.9) by 2 \( \delta t e_{h|0}^{k+1} \)

\[ (6.12) \quad | e_{h|0}^{k+1} |^2 + | e_{h|0}^{k+1} - i_h^{k+1} |^2 - | e_{h|0}^{k+1} |^2 = 0. \]

(e) After summing up (6.10) + (6.11) + (6.12) we obtain

\[ | e_{h|0}^{k+1} |^2 + \delta t^2 | C_{h|0}^{r} e_{h|0}^{k+1} |^2 + 2 \alpha \delta t | e_{h|0}^{k+1} |^2 \leq | e_{h|0}^{k+1} |^2 + (1 + \delta t) \delta t^2 | C_{h|0}^{r} e_{h|0}^{k+1} |^2 + c\delta t^3. \]

By taking the sum from \( k = k_0 \) to some integer \( n \leq K \) we obtain

\[ | e_{h}^{n+1} |^2 + \delta t^2 | C_{h}^{r} e_{h|0}^{n+1} |^2 + 2 \alpha \delta t \sum_{k = k_0}^{n} | e_{h|0}^{k+1} |^2 \leq | e_{h|0}^{k+1} |^2 + \delta t^2 | C_{h}^{r} e_{h|0}^{k+1} |^2 + c\delta t^2 \]

\[ + \delta t \sum_{k = k_0}^{n} [ \delta t^2 | C_{h}^{r} e_{h|0}^{k+1} |^2 ]. \]

By our particular choice of the initial conditions we have

\[ | e_{h}^{k_0} | = 0 \quad \text{and} \quad | C_{h}^{r} e_{h|0}^{k_0} | = 0. \]
As a result, the discrete Gronwall lemma yields

\[(6.13) \quad |e^{n+1}_h|_0^2 + \delta t \sum_{k=k_0}^{n} |\tilde{e}^{k+1}_h|_1^2 \leq c \delta t^2.\]

The final result is a consequence of

\[u(t^k) - u^k = e^k_h + u(t^k) - w^k_h, \quad u(t^k) - \tilde{u}^k = \tilde{e}^k_h + u(t^k) - w^k_h,\]

together with the convergence hypothesis (6.5). \(\square\)

The ability of \(\delta_t u^{k+1}_h/\delta t\) to approximate \(\delta_t w^{k+1}_h/\delta t\) is explicited by

**Proposition 6.1:** If \(\delta t\) is small enough, the solution to the projection scheme (6.2)-(6.3) satisfies:

\[(6.14) \quad \max_{k_0 \leq k \leq K} \left[ |\delta_t e^k_h|_0 + \delta t \sum_{k=k_0}^{K} |\delta_t \tilde{e}^k_h|^2_1 \right]^{1/2} \leq c \delta t^2.\]

**Proof:** (a) In a first step we control \(\delta_t \tilde{e}^{k_0+1}_h, \delta_t e^{k_0+1}_h\) and \(\delta_t e^{k_0+1}_h\). We note first that

\[|\tilde{e}^{k_0+1}_h|^2_0 \leq |\tilde{e}^{k_0}_h|^2_0 - 2 \delta t (\tilde{e}^{k_0+1}_h, B'_h \psi^{k_0}_h) \leq -2 \delta t (\tilde{e}^{k_0+1}_h, B'_h [\delta_t q^{k_0+1}_h + e^{k_0}_h]) \leq \frac{1}{2} |\tilde{e}^{k_0+1}_h|^2_0 + c \delta t^4.\]

We obtain the bound

\[|\tilde{e}^{k_0+1}_h|_0 \leq c \delta t^2,\]

which yields

\[(6.15) \quad |\delta_t \tilde{e}^{k_0+1}_h|_0 \leq c \delta t^2.\]

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Furthermore, from the projection step (6.9) we obtain

\[
\begin{align*}
|\varepsilon_h^{k+1}|_0 & \leq |\tilde{\varepsilon}_h^{k+1}|_0, \\
|C_h' (\phi_h^{k+1} - \psi_h^k)|_0 & \leq |\tilde{\varepsilon}_h^{k+1}|_0 \delta t.
\end{align*}
\]

The first bound easily yields

\[(6.16) \quad |\delta_t \varepsilon_h^{k+1}|_0 \leq c \delta t^2.\]

The other bound yields

\[
|C_h' (\phi_h^{k+1} - \psi_h^k)|_0 \leq |\tilde{\varepsilon}_h^{k+1}|_0 \delta t + |C_h' \delta_t \phi_h^{k+1}|_0
\]

\[
\leq c \delta t.
\]

If other words, we have

\[(6.17) \quad |C_h' \delta_t \phi_h^{k+1}|_0 \leq c \delta t.\]

(b) Now we proceed as in the proof of theorem 6.1. For \(k \geq k_0 + 1\), the equation which controls the error \(\delta_t \varepsilon_h^{k+1}\) is

\[(6.18) \quad \frac{\delta_t \varepsilon_h^{k+1} - \delta_t \phi_h^k}{\delta t} + A_h \delta_t \varepsilon_h^{k+1} + B_h \delta_t \psi_h^k = 0,\]

and the system of equations which controls \(\delta_t \varepsilon_h^k\) and \(\delta_t \phi_h^k\) is found to be

\[(6.19) \quad \begin{cases}
\delta_t \varepsilon_h^{k+1} - i_h \delta_t \phi_h^{k+1} \\
C_h' \delta_t \varepsilon_h^k + C_h' [\delta_t \phi_h^{k+1} - \delta_t \psi_h^k] = 0,
\end{cases}\]

\(C_h' \delta_t \varepsilon_h^{k+1} = 0.\)

(c) By reasoning as in the proof of theorem 6.1, we see that the final bound is a consequence of (a) and (b). \(\square\)
We are now in measure of establishing a convergence result on the pressure.

**Theorem 6.2.** The approximate pressure given by the projection scheme (6.2)-(6.3) satisfies

\[
\left[ \delta t \sum_{k=0}^{K} \left| p(t^k) - p_h^k \right|^2 \right]^{1/2} \leq c(\delta t + h).
\]

**Proof:** By summing (6.8) and (6.9), and using the relation \( i_h' C_h^l = B_h^l \), we obtain

\[
B_h^l \epsilon_{h}^{k+1} = - \frac{i_h' \delta t e_{h}^{k+1}}{\delta t} - A_h \epsilon_{h}^{k+1}.
\]

The inf-sup condition on \( B_h^l : M_h \to X_h' \) implies that

\[
c_1 |\epsilon_{h}^{k}|_0 \leq \frac{|\delta t e_{h}^{k+1}|_0}{\delta t} + c_2 |\epsilon_{h}^{k+1}|_1.
\]

The final bound is a consequence of this inequality and (6.13), (6.14) together with the convergence hypothesis (6.5) and the identity

\[
p(t^k) - p_h^k = \epsilon_{h}^{k} + p(t^k) - q_h^k
\]

Note that in order to obtain an error estimate on the pressure we have reconstructed an approximation of the momentum equation (6.21), by combining the viscous step (6.8) and the projection step (6.9). The discrete momentum equation (6.21) clearly shows that the discrete gradient operator which comes into play is not \( C_h^l : M_h \to Y_h \) but \( B_h^l : M_h \to X_h' \). Hence, although the fractional steps (6.2)-(6.3) do not seem to require \( B_h^l \) to be onto, convergence in time is ensured only if \( X_h \) and \( M_h \) satisfy an inf-sup condition.

### 7. Relationship with Some Uzawa Preconditioning

We show in this section how the three projection algorithms presented above can be interpreted as particular preconditioning techniques.

Our starting point is still the time-dependent Stokes problem (2.11). Assume we wish to approximate it by means of the one step backward Euler scheme (6.4). The formulation (6.4) is classical; it couples the pressure and the velocity by means of the kinematical constraint \( B_h w_h^{k+1} = 0 \). One way of
looking at this problem consists in eliminating the velocity by means of a Gauss elimination, for the first pivot in the system \((6.4)\), \(I_d/\delta t + A_h\) is invertible. As a result the problem \((6.4)\) consists in finding the pressure field \(q_h^{k+1}\) so that

\[
B_h(I_d - \delta t A_h)^{-1} B'_h(q_h^{k+1}) = \frac{1}{\delta t} B_h(I_d - \delta t A_h)^{-1} (\delta t f_h^{k+1} + w_h^k)
\]

In the literature, the operator \(B_h(I_d - \delta t A_h)^{-1} B'_h\) is frequently referred to as the Uzawa operator, it is hereafter denoted by \(U_{\delta t}\). Note that this operator has a condition number of \(O(1)\) if \(\delta t\) is of \(O(1)\). However, \(\delta t\) is bound to tend to zero. As a result, the condition number of \(U_{\delta t}\) is very large in practice, and iterative solutions of \((7.1)\) are possible only if \(U_{\delta t}\) is preconditioned. If a preconditioner were at hand, one crude iterative technique would consist of Picard iterations. In the following we show how such an algorithm can be implemented.

Assume that \(q_h^k\) is the first guess of the pressure, then the pressure increment, \(q_h^{k+1} - q_h^k\), is solution to

\[
U_{\delta t}(q_h^{k+1} - q_h^k) = \frac{B_h\tilde{u}_h^{k+1}}{\delta t},
\]

where we have set \(\tilde{u}_h^{k+1} = (I_d - \delta t A_h)^{-1} (\delta t q_h^{k+1} + w_h^k - \delta t B'_h q_h^k)\), in other words, \(\tilde{u}_h^{k+1} \in X\) is the solution to

\[
\frac{\tilde{u}_h^{k+1} - w_h^k}{\delta t} + A_h\tilde{u}_h^{k+1} + B'_h q_h^k = f_h^{k+1}
\]

Note that this problem coincides exactly with the provisional step of the three projection algorithms studied in the previous sections.

The difficult task, now, consists in solving \((7.2)\) approximately. One possibility consists in assuming that if \(\delta t\) is small, \(U_{\delta t}\) should not be very different from \(U_0 = B_h B'_h\). As a result, if \(\delta t\) is small enough, it is legitimate to solve approximately the pressure problem in the following form (see e g [13])

\[
B_h B'_h(p_h^{k+1} - q_h^k) = \frac{B_h\tilde{u}_h^{k+1}}{\delta t}
\]

Note that \((7.4)\) is equivalent to the projection step of the first algorithm. Likewise, by defining \(C_h\) as the discrete divergence operator introduced in the second projection algorithm \((4.5)\), an other preconditioning technique consists in solving

\[
C_h C'_h(p_h^{k+1} - q_h^k) = \frac{B_h\tilde{u}_h^{k+1}}{\delta t}
\]
This approximate solution corresponds to the projection step of the second algorithm. A third alternative that is equivalent to the projection step of the third algorithm consists in solving

\[ D_h(p_h^{k+1} - q_h^k) = \frac{B_h u_h^{k+1}}{\delta t} \]

In conclusion, one may interpret the projection step of the three projection algorithms presented above as a one step preconditioned Picard iteration on \( U_{ot} \), the three preconditioners being either \( B_h, B'_h, C_h, C'_h \) or \( D_h \). Note also that if instead of \( q_h^k \), the first guess of the pressure is zero, the preconditioning techniques in question reduce to the non incremental version of the three projection algorithms (see Cahouet-Chabard [6], Guermond [14] or Lababie-Lasbleiz [17] for other details on these preconditioners) Incidentally, it is shown in [6] and confirmed in [14] that \( B_h, B'_h \) is really a preconditioner of \( U_{ot} \) in purely algebraic terms only if \( \delta t \) is very small, for finite elements this condition reads \( \delta t \leq ch^3 \). The fact that such a condition did not show up in the analysis of the stability of projection algorithms may possibly mean that \( B_h, B'_h \) acts as a preconditioner of \( U_{ot} \) if the spatial spectral content of the right hand side is dominated by low frequencies.

The next and final step consists in correcting the provisional velocity \( \tilde{u}_h^{k+1} \). In a pure fixed point strategy, the end-of-step velocity should be set to

\[ \left( I_d - \delta t A_h \right)^{-1} \left( \delta t \tilde{u}_h^{k+1} + w_h^k - \delta t B'_h p_h^{k+1} \right), \]

and depending on the satisfaction of some convergence criterion, new iterations could be performed as advocated in [2]. It is at this very point that classical iterative techniques differ from the projection techniques. Actually, if the velocity is corrected as suggested above, the stability on the discrete divergence of this velocity cannot be ensured in only one step. As a consequence, in practical this technique requires more than one iteration (see Cahouet-Chabard [6] or Lababie-Lasbleiz [17] for other details on this technique). In contrast, the distinctive feature of projection algorithms is that the provisional velocity \( \tilde{u}_h^{k+1} \) is corrected in a way so that the new velocity is discretely divergence free (see second equation in (3.3) and (4.5) and (5.7) in proposition 5.1), the consequence being that the scheme is stable and converges (i.e. reaches the consistency level) in only one iteration per time step.

Finally, note that when it comes to implementing the three projection algorithms described above, it is not necessary to calculate explicitly the end-of-step velocities \( (u_h^k)_{k=0}^K \) since they can be eliminated. Indeed, by replacing the velocity \( u_h^k \) in the prediction steps (3.2), (4.4) or (5.4) by its value calculated at the previous projection step (3.3), (4.5) or (5.6) one obtains

\[ \frac{\tilde{u}_h^{k+1} - \tilde{u}_h^k}{\delta t} + A_h \tilde{u}_h^{k+1} = f_h^{k+1} - B'_h (2 p_h^k - p_h^{k-1}) \]
(7.8) \[ C_h C'_h(p_h^{k+1} - p_h^k) = \frac{B_h u_h^{k+1}}{\delta t}, \]

where \( C_h \) denotes any extension of \( B_h \) that has already been defined.

**Proof**: This is a consequence of the fact that \( i_h^t u_h^k = \bar{u}_h^k \) and \( i_h^t C'_h = B'_h. \) □

This remark means that in practice the possibly weird space \( Y_h \) is never used.

Once again, this algorithm could be interpreted as a one step preconditioned Picard algorithm if the initial guess \( q_h^k \) in (7.8) was replaced by \( 2p_h^k - p_h^{k-1} \), but in this case the algorithm would not be stable. Global stability is ensured by taking \( q_h^k = 2p_h^k - p_h^{k-1} \) in the first step (7.7) and \( q_h^k = p_h^k \) in the second step (7.8).

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**REFERENCES**


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