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MULTI-PARAMETER ASYMPTOTIC ERROR RESOLUTION OF THE MIXED FINITE ELEMENT METHOD FOR THE STOKES PROBLEM

AIHUI ZHOU¹

Abstract. In this paper, a multi-parameter error resolution technique is applied into a mixed finite element method for the Stokes problem. By using this technique and establishing a multi-parameter asymptotic error expansion for the mixed finite element method, an approximation of higher accuracy is obtained by multi-processor computers in parallel.

Résumé. Dans cet article une méthode de résolution d’erreurs multi-paramétrique est appliquée à la méthode des éléments finis mixte pour le problème de Stokes. À l’aide de cette technique, et en utilisant un développement asymptotique multi-paramétrique de l’erreur, on obtient une plus grande précision par calcul parallèle sur des machines multi-processeurs.

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1. INTRODUCTION

The Stokes equations have become an important model problem in computational fluid dynamics for designing and analyzing finite element algorithms. In the context of the Galerkin variational formulation, the computational accuracy for the velocity components can be compared to that known for the Poisson equation. For the pressure, however, one frequently observes a drastic reduction of the accuracy along the boundary. Therefore, one has anyway to employ some techniques or arguments to recover and increase the accuracy.

The extrapolation approach established by Richardson in 1926, is an important technique to obtain approximations of higher accuracy. The application of this approach in the finite difference method can be found in [13]. In 1983, Lin, Lü and Shen [10] have applied the technique to the finite element method. Development in this direction can be found in [3,12,14]. However, this approach has a limitation since it requires a global refinement and hence wastes computing time and memory. Recently, a so-called multi-parameter error resolution technique has been introduced to obtain approximations of higher accuracy (see [19,20]). This new approach is based on a multi-parameter asymptotic error expansion and only uses partial refinements. It is shown that a combination of discrete solutions related to such partial refinements can produce an approximation of higher accuracy and the procedure can be done by multi-processor computers in parallel. In this paper, we apply this technique to a mixed finite element method for the Stokes problem.

Consider the homogenous Stokes problem

\[
\begin{align*}
-\Delta \mathbf{u} + \nabla p &= \mathbf{f}, & \text{in } \Omega, \\
\text{div } \mathbf{u} &= 0, & \text{in } \Omega, \\
\mathbf{u} &= 0, & \text{on } \partial \Omega,
\end{align*}
\]

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where \( \Omega = [0,1]^2 \), \( u = (u_1,u_2) \) is the velocity, \( p \) is the pressure and \( f \) indicates the external force. We know that (1.1) is equivalent to the variational formulation (8): Find \((u,p) \in (H^1_0(\Omega))^2 \times L^2_0(\Omega)\) such that

\[
B(u,p;v,q) = (f,v), \quad \forall (v,q) \in (H^1_0(\Omega))^2 \times L^2_0(\Omega),
\]

where

\[
B(u,p;v,q) = (\nabla u, \nabla v) - (p, \text{div} v) + (q, \text{div} u)
\]

and other notations are identical to those of references [5,8].

Divide \( \Omega \) into subrectangles \( \Omega_j (j = 1, \cdots, m) \) whose edges are parallel to the \( x \)-axis and the \( y \)-axis respectively. On each \( \Omega_j (j = 1, \cdots, m) \) a uniform mesh is imposed, and globally a quasi-uniform partition on \( \Omega \) is formed. Denote the mesh sizes on \( \Omega_j \) by \( h_{j,1} \) in \( x \)-direction and \( h_{j,2} \) in \( y \)-direction \((j = 1, \cdots, m)\). Among these mesh parameters, some are independent, say \( h_1, \cdots, h_s \). It can be proved that \( 2 \leq s \leq m + 1 \) and one can choose \( s > 2 \). Let \( h = \max \{h_{j,1}, \cdots, h_s\}, T_h \) be the partition on \( \Omega \) and \((\nabla_h, L_h)\) be a pair of finite element spaces on \( T_h \), e.g. the Bernardi-Raugel finite element space or the filtered bilinear-constant finite element space, satisfying the Babuska-Brezzi condition (see [2,8]). The interpolated finite element approximations corresponding to \( h_1, \cdots, h_s \) is denoted by \((u(h_1, \cdots, h_s), p(h_1, \cdots, h_s))\). Then there exist multi-parameter error resolution expressions on \( \Omega \) (see Sect. 4)

\[
\begin{align*}
\mathbf{u}(h_1, \cdots, h_s) &= u + \sum_{j=1}^{s} a_j h_j^2 + O(h^3), \text{ in } H^1 \text{- norm,} \\
\mathbf{u}(h_1, \cdots, h_s) &= u + \sum_{j=1}^{s} a_j h_j^2 + O(h^4), \text{ in } L^2 \text{- norm,} \\
p(h_1, \cdots, h_s) &= p + \sum_{j=1}^{s} b_j h_j^2 + O(h^3), \text{ in } L^2 \text{- norm}
\end{align*}
\]

where \( a_j, b_j (j = 1, \cdots, s) \) are independent of \((h_1, \cdots, h_s)\). Based on (1.3), a multi-parameter extrapolation yields approximations of higher accuracy

\[
\begin{align*}
(4 \sum_{j=1}^{s} u_j - (4s - 3)u_0)/3 &= u + O(h^3), \text{ in } H^1 \text{- norm,} \\
(4 \sum_{j=1}^{s} u_j - (4s - 3)u_0)/3 &= u + O(h^4), \text{ in } L^2 \text{- norm,} \\
(4 \sum_{j=1}^{s} p_j - (4s - 3)p_0)/3 &= p + O(h^3), \text{ in } L^2 \text{- norm,}
\end{align*}
\]

where \((u_0, p_0) = (u(h_1, \cdots, h_s), p(h_1, \cdots, h_s))\) and \((u_j, p_j) = (u(h_1, \cdots, h_{j-1}, h_{j}/2, h_{j+1}, \cdots, h_s), p(h_1, \cdots, h_{j-1}, h_{j}/2, h_{j+1}, \cdots, h_s))\). Therefore, a parallel algorithm for approximations of higher accuracy can be designed as follows.

**Algorithm.**

*Step 1.* Compute \((u_j, p_j)(0 \leq j \leq s)\) in parallel.

*Step 2.* Set

\[
\begin{align*}
\mathbf{u}^c &= (4 \sum_{j=1}^{s} u_j - (4s - 3)u_0)/3, \\
p^c &= (4 \sum_{j=1}^{s} p_j - (4s - 3)p_0)/3.
\end{align*}
\]
2. Preliminaries

For any element $e = [x_e - h_e, y_e - k_e]^2$, we define the interpolation operators $i_h = (i_{h,1}, i_{h,2}) : (C(e))^2 \rightarrow Q_{1,2} \times Q_{2,1}$ and $j_h : L^2(e) \rightarrow Q_0$ by (cf. [2,8])

$$
\left\{ \begin{array}{l}
(v - i_h v)(x_e \pm h_e, y_e \pm k_e) = 0, \forall v \in (C(e))^2, \\
\int_{(x_e \pm h_e, y_e \pm k_e)} (\varphi - i_{h,1} \varphi) dy = 0, \forall \varphi \in C(e), \\
\int_{(x_e \pm h_e, y_e \pm k_e)} (\varphi - i_{h,2} \varphi) dx = 0, \forall \varphi \in C(e),
\end{array} \right.
$$

where $Q_{r,n} = \text{span}\{x^i y^j : 0 \leq i \leq r, 0 \leq j \leq n\}$ and $Q_r = Q_{r,r}$. Introduce two other postprocessing interpolation operators. Let $T_h$ be a rectangular partition on $\Omega$ with size $h$. We assume that $T_h$ has been obtained from $T_{3h}$ by dividing each element into nine congruent rectangles. Let $\tau = \bigcup_{i=1}^9 e_i \in T_{3h}$ with $e_i \in T_h$, and $I_{3h} = (I_{3h,1}, I_{3h,2})$ and $J_{3h}$ are defined as

$$
\left\{ \begin{array}{l}
I_{3h,j} w|_e \in Q_3(\tau), j = 1, 2, \\
I_{3h,j} w(p_i) = w(p_i), i = 1, \cdots, 16, j = 1, 2,
\end{array} \right.
$$

where $p_i (i = 1, \cdots, 16)$ are all vertices of $e_1, \cdots, e_9$. It can be proved that (cf. [11,17,18])

$$
\left\{ \begin{array}{l}
I_{3h} i_h = I_{3h}, \\
\|I_{3h} v\|_1 \leq c \|v\|_1, \forall v \in V_h, \\
h^{-1}\|I_{3h} w - w\|_0 + \|I_{3h} w - w\|_1 \leq ch^r\|w\|_{1+r}, \forall w \in H^{1+r}(\Omega), 1 \leq r \leq 3,
\end{array} \right.
$$

$$
\left\{ \begin{array}{l}
J_{3h} j_h = J_{3h}, \\
\|J_{3h} q\|_0 \leq c \|q\|_0, \forall q \in L_h, \\
\|J_{3h} w - w\|_0 \leq ch^r\|w\|_r, \forall w \in H^r(\Omega), 1 \leq r \leq 3.
\end{array} \right.
$$

In order to solve the problem (1.1), many pairs of finite element spaces were introduced (see [2,8]). One of them is the so-called Bernardi-Raugel element, which is defined by

$$
\left\{ \begin{array}{l}
V_h = \{v \in (C(\bar{\Omega}))^2, v|_e \in Q_{1,2}(e) \times Q_{2,1}(e), v|_{\partial\Omega} = 0, e \in T_h\}, \\
L_h = \{q \in L_0^2(\Omega), q|_e \in Q_0(e), \int_{\Omega} q = 0, e \in T_h\}.
\end{array} \right.
$$

We mention here that the Bernardi-Raugel element was presented but not analysed in [7].
3. ERROR RESOLUTION FOR INTERPOLANTS

We have the following *multi-parameter error resolution* for interpolants.

**Theorem 3.1.** For \((u, p) \in (H^4(\Omega))^2 \times H^3(\Omega)\), there exist \(f_j \in (L^2(\Omega))^2, g_j \in (H^{1/2}(\Gamma))^2 (j = 1, \ldots, s)\) such that

\[
B(u - i_h u, p - j_h p; v, q) = \sum_{j=1}^{s} h_j^2 \left( \int_{\Omega} f_j v + \int_{\Gamma} g_j v \right) + O(h^3)(\|u\|_4 + \|p\|_3)\|v\|_1, \forall (v, q) \in V_h \times L_h,
\]

where \(\Gamma = \cup_{1 \leq i, j \leq s} \partial \Omega_i \cap \partial \Omega_j\).

**Proof.** Since

\[
(q, \text{div} (u - i_h u)) = 0, \quad \forall q \in L_h,
\]

it is only necessary to prove two expansions

\[
(\nabla (u - i_h u), \nabla v) = \frac{1}{3} \sum_{e \in T_h} \int_{e} (h_e^2 \partial_{xxyy} u_1, k_e^2 \partial_{xxyy} u_2) v + O(h^3)\|u\|_4\|v\|_1
\]

for \(v = (v_1, v_2) \in V_h\), and

\[
(p - j_h p, \text{div} v) = \frac{1}{3} \sum_{e \in T_h} \int_{e} (k_e^2 \partial_{xxyy} p, h_e^2 \partial_{xxyy} p) v - \frac{1}{3} \sum_{s_{e,4} \cup s_{e,2} \subset \Gamma_x} k_e^2 \int_{s_{e,4}} \int_{s_{e,2} \subset \Gamma_y} \partial_{xxyy} p v_1
\]

\[
- \frac{1}{3} \sum_{s_{e,3} \cup s_{e,1} \subset \Gamma_y} h_e^2 \left( \int_{s_{e,3}} - \int_{s_{e,1}} \right) \partial_{xxyy} p v_2 + O(h^3)\|p\|_3\|v\|_1,
\]

where \(\Gamma_x, \Gamma_y\) is the part of \(\Gamma\) parallel to the \(x\)-direction and the \(y\)-direction respectively, and

\[
s_{e,1} = \{(x, y) : x = x_e - h_e, y_e - k_e \leq y \leq y_e + k_e\},
\]

\[
s_{e,2} = \{(x, y) : x_e - h_e \leq x \leq x_e + h_e, y = y_e + k_e\},
\]

\[
s_{e,3} = \{(x, y) : x = x_e + h_e, y_e - k_e \leq y \leq y_e + k_e\},
\]

\[
s_{e,4} = \{(x, y) : x_e - h_e \leq x \leq x_e + h_e, y = y_e + k_e\}.
\]

We employ the technique in [11,17,18] and introduce the two error functions

\[
F = F_e = \frac{1}{2}((y - y_e)^2 - h_e^2), \quad E = E_e = \frac{1}{2}((x - x_e)^2 - h_e^2),
\]

then, it is obvious that \(F(y) = 0\) on \(s_{e,2}\) and \(s_{e,4}\), \(E(x) = 0\) on \(s_{e,1}\) and \(s_{e,3}\).
Let \( u = (u_1, u_2) \), we only need to prove
\[
\int e \partial_x (u_1 - i_{h,1} u_1) \partial_x v_1(x, y) = 0.
\]

A Taylor expansion yields
\[
\partial_x v_1 = \partial_x v_1(x, y) + \frac{1}{6} (F^2)_{yyy} \partial_{xy} v_1(x, y) + \frac{1}{90} (F^3)_{yyyy} + \frac{1}{10} k_e \partial_{xy} v_1.
\]

The definition (2.1), integration by parts and inverse estimates lead to
\[
\int e \partial_x (u_1 - i_{h,1} u_1) \partial_x v_1(x, y) = 0,
\]
\[
\int e (F^2)_{yyyy} \partial_x (u_1 - i_{h,1} u_1) \partial_{xy} v_1(x, y) = -\frac{1}{6} \int e F^2 \partial_{xy} u_1 \partial_{xy} v_1(x, y) = O(h^3) \|u\|_4 \|v\|_1,
\]
\[
\int e \partial_x (u_1 - i_{h,1} u_1) \left( \frac{1}{90} (F^3)_{yyyy} + \frac{1}{10} k_e \right) \partial_{xy} v_1 = -\frac{1}{90} \int e (F^3)_{yyyy} u_1 \partial_{xy} v_1 = O(h^3) \|u\|_4 \|v\|_1.
\]

Thus, we obtain
\[
(\partial_x (u_1 - i_{h,1} u_1), \partial_x v_1) = O(h^3) \|u\|_4 \|v\|_1
\]  (3.4)

For \((\partial_y (u_1 - i_{h,1} u_1), \partial_y v_1)\), using the definition (2.1),
\[
\partial_y v_1 = E_{xx} \partial_y v_1(x, y) + \frac{1}{6} (E^2)_{xxx} \partial_{xy} v_1,
\]
and integration by parts,
\[
\int e \partial_y (u_1 - i_{h,1} u_1) (E)_{xx} \partial_y v_1(x, y)
\]
\[
= -\left( \int_{s_{e,3}} - \int_{s_{e,1}} \right) E_x \partial_y (u_1 - i_{h,1} u_1) \partial_y v_1(x, y) dy - \int e E_x \partial_{xy} (u_1 - i_{h,1} u_1) \partial_y v_1(x, y)
\]
\[
= -\int_{s_{e,3}} - \int_{s_{e,1}} E_x (u_1 - i_{h,1} u_1) \partial_{xy} v_1(x, y) dy + \int e E \partial_{xy} u_1 \partial_y v_1(x, y)
\]
\[
= -\frac{1}{3} h_e^2 \int e \partial_{xy} u_1 \partial_y v_1 - E_x \partial_{xy} v_1 + \frac{1}{6} \int e (E^2)_{xx} \partial_{xy} u_1 \partial_y v(x, y)
\]
\[
= -\frac{1}{3} h_e^2 \int e \partial_{xy} u_1 \partial_y v_1 + \int e \partial_{zxy} u_1 \left( \frac{1}{3} h_e^2 E \partial_{xy} v_1 - \frac{1}{6} (E^2)_{x} \partial_y v_1 + \frac{1}{6} (E^2)_{x} E \partial_{xy} v_1 \right)
\]
\[
= -\frac{1}{3} h_e^2 \int_{s_{e,3}} - \int_{s_{e,1}} \partial_{xy} u_1 v_1 dx + \frac{1}{3} h_e^2 \int e \partial_{zxy} u_1 v_1 + O(h^3) \|u\|_4 \|v\|_1,
\]
\[
\frac{1}{6} \int (E^2)_{xx} \partial_y (u_1 - i_h u_1) \partial_{xy} v_1 \\
= \frac{1}{6} \left( \int_{s_{e,3}} - \int_{s_{e,1}} (E^2)_{xx} \partial_y (u_1 - i_h u_1) \partial_{xy} v_1 - \frac{1}{6} \int_e (E^2)_{xx} \partial_y (u_1 - i_h, u_1) \partial_{xy} v_1 \right) \\
= -\frac{1}{6} \left( \int_{s_{e,3}} - \int_{s_{e,1}} (E^2)_{xx} (u_1 - i_h u_1) \partial_{xy} v_1 + \frac{1}{6} \int_e (E^2)_{x} \partial_{xxy} u_1 \partial_{xy} v_1 \right) \\
= \frac{1}{6} \int_e (E^2)_{x} \partial_{xxy} u_1 \partial_{xy} v_1 \\
= O(h^3) \|u\|_4 \|v\|_1.
\]

Therefore, we have

\[
(\partial_y (u_1 - i_h u_1), \partial_y v_1) = \frac{1}{3} \sum_{e \in T_h} h_e^2 \left( \int_{s_{e,1}} - \int_{s_{e,4}} \right) \partial_{xxy} u_1 \partial_{xy} v_1 dx + \int_e \partial_{xxy} u_1 \partial_{xy} v_1 \\
+ O(h^3) \|u\|_4 \|v\|_1.
\]

(3.5)

By the quasi-uniformity of \( T_h \), one sees that line integrals in (3.5) disappear during the summation, thus (3.3) follows from (3.4, 3.5).

We turn to prove (3.2). Similar to the proof of (3.1), we only need to prove

\[
(p - j_h p, \partial_x v_1) = \frac{1}{3} \sum_{e \in T_h} h_e^2 \left( \int_{s_{e,1}} - \int_{s_{e,4}} \right) \partial_{xxy} p \partial_{xy} v_1 dx + \int_e \partial_{xxy} p \partial_{xy} v_1 \\
+ O(h^3) \|p\|_3 \|v\|_1.
\]

(3.6)

By the Taylor expansion, we have

\[
\int_e (p - j_h p) \partial_x v_1 = \int_e (p - j_h p) (\partial_x v_1 (x, y_e) + F_y \partial_{xy} v_1 (x, y_e) + \frac{1}{6} ((F^2)_{yy} + k_e^2) \partial_{xyy} v_1) \\
= I + II + III.
\]

(3.7)

The definition (2.2) shows that \( I = 0 \) and

\[
II = - \int_e F \partial_y p \partial_{xy} v_1 (x, y_e) \\
= \frac{1}{3} k_e^2 \int_e \partial_y p \partial_{xy} v_1 (x, y_e) - \frac{1}{6} \int_e (F^2)_{yy} \partial_y p \partial_{xy} v_1 (x, y_e) \\
= \frac{1}{3} k_e^2 \left( \int_{s_{e,3}} - \int_{s_{e,1}} \right) \partial_y p \partial_{xy} v_1 (x, y_e) dy - \frac{1}{3} k_e^2 \int_e \partial_{xy} p (\partial_y v_1 - F_y \partial_{xy} v_1) + O(h^3) \|p\|_3 \|v\|_1 \\
= \frac{1}{3} k_e^2 \left( \int_{s_{e,3}} - \int_{s_{e,1}} \right) \partial_y p \partial_{xy} v_1 (x, y_e) dy - \frac{1}{3} k_e^2 \int_e \partial_{xy} p \partial_{xy} v_1 + O(h^3) \|p\|_3 \|v\|_1 \\
= \frac{1}{3} k_e^2 \left( \int_{s_{e,3}} - \int_{s_{e,1}} \right) \partial_y p \partial_{xy} v_1 (x, y_e) dy - \frac{1}{3} k_e^2 \left( \int_{s_{e,4}} - \int_{s_{e,2}} \right) \partial_{xy} p \partial_{xy} v_1 dx \\
+ \frac{1}{3} k_e^2 \int_e \partial_{xyy} p \partial_{xy} v_1 + O(h^3) \|p\|_3 \|v\|_1.
\]
\[ III = \frac{1}{6} \int_{\Omega} F^2 \partial_{xyy} \partial_{xyy} v_1 \]
\[ = \frac{1}{6} \left( \int_{S_e,3} - \int_{S_e,1} \right) F^2 \partial_{xyy} \partial_{xyy} v_1 dy - \frac{1}{6} \int_{S_e} F^2 \partial_{xyy} \partial_{xyy} v_1 dy \]
\[ = \frac{1}{6} \left( \int_{S_e,3} - \int_{S_e,1} \right) F^2 \partial_{xyy} \partial_{xyy} v_1 dy + O(h^3) \|p\|_3 \|v\|_1. \]

Similarly, line integrals along y-direction in the above terms will disappear during the summation of e \( \in T_h \). Thus we complete the proof.

From the proof of Theorem 3.1, we can also obtain the following

**Theorem 3.2.** For \((u,p) \in (H^4(\Omega))^2 \times H^3(\Omega), \) there exist \(f_j \in (L^2(\Omega))^2, g_j \in (H^{1/2}(\Gamma))^2(j = 1, \cdots, s)\) such that

\[ B(u - i_h u, p - j_h p; v, q) = \sum_{j=1}^s h_j^2 \left( \int_\Omega f_j v + \int_{\Gamma} g_j v \right) \]
\[ + O(h^4)(\|u\|_4 + \|p\|_3)(h^{-1}\|v - w\|_1 + \|w\|_2), \forall (v,q) \in V_h \times L_h, \quad (3.8) \]

where \(w \in (H^1_0(\Omega) \cap H^4(\Omega))^2.\)

### 4. Error Resolution for Finite Element Solutions

A mixed finite element method based on (1.1) reads as follows: Find \((u_h, p_h) \in V_h \times L_h\) such that

\[ B(u_h, p_h; v, q) = (f, v), \quad \forall (v,q) \in V_h \times L_h. \quad (4.1) \]

or

\[ B(u_h - u, p_h - p; v, q) = 0, \quad \forall (v,q) \in V_h \times L_h. \quad (4.2) \]

One has the following error estimate (see [2,8])

\[ h^{-1}\|u - u_h\|_0 + \|u - u_h\|_1 + \|p - p_h\|_0 \leq c h (\|u\|_2 + \|p\|_1). \]

(4.3)

Now, we shall present the multi-parameter error resolution for the numerical solution.

**Theorem 4.1.** If \((u,p) \in (H^1_0(\Omega) \cap H^4(\Omega))^2 \times (L^2_0(\Omega) \cap H^3(\Omega))^2)\) is the exact solution of (1.1), then there exist \((a_j, b_j) \in (H^1_0(\Omega) \cap H^2(\Omega \setminus \Gamma))^2 \times (L^2_0(\Omega) \cap H^1(\Omega \setminus \Gamma))^2(j = 1, \cdots, s)\) such that

\[ I_{3h} u - u = \sum_{j=1}^s a_j h_j^2 + O(h^3), \quad \text{in } H^1(\Omega \setminus \Gamma) \]
\[ J_{3h} p_h - p = \sum_{j=1}^s b_j h_j^2 + O(h^3), \quad \text{in } L^2(\Omega \setminus \Gamma). \]

**Proof.** Let \((a_j, b_j) \in (H^1_0(\Omega))^2 \times L^2_0(\Omega)(j = 1, \cdots, s)\) satisfy

\[ B(a_j, b_j; v, q) = (f_j, v) + \int_{\Gamma} g_j v, \forall (v,q) \in (H^1_0(\Omega))^2 \times L^2_0(\Omega) \]

(4.4)

and \((a_{jh}, b_{jh}) \in V_h \times L_h (j = 1, \cdots, s)\)

\[ B(a_{jh, b_{jh}; v, q}) = (f_j, v) + \int_{\Gamma} g_j v, \forall (v,q) \in V_h \times L_h, \]

(4.5)
then we have

\[ B(u - i_h u - \sum_{j=1}^s a_{j,h} h_j^2, p - j_h p - \sum_{j=1}^s b_{j,h} h_j^2; v, q) = O(h^3)\|v\|_1. \]

Taking \( v = u_h - i_h u - \sum_{j=1}^s a_{j,h} h_j^2 \) and \( q = p_h - j_h p - \sum_{j=1}^s b_{j,h} h_j^2 \) in the above equation, we obtain by (4.2) and the Babuska-Brezzi condition (see e.g. [1, 2, 4])

\[
\begin{align*}
\begin{cases}
  u_h - i_h u = \sum_{j=1}^s a_{j,h} h_j^2 + O(h^3), \text{ in } H^1(\Omega), \\
p_h - j_h p = \sum_{j=1}^s b_{j,h} h_j^2 + O(h^3), \text{ in } L^2(\Omega).
\end{cases}
\end{align*}
\]

(4.6)

Regularity results imply that \( (a_j, b_j) \in (H^1_0(\Omega) \cap H^2(\Omega \setminus \Gamma))^2 \times (L^2_0(\Omega) \cap H^1(\Omega \setminus \Gamma))(j = 1, \cdots, s) \) (see [9]) and a similar estimate to (4.3) yields

\[
\|a_j - a_{j,h}\|_1 + \|b_j - b_{j,h}\|_0 \leq ch(\|a_j\|_2 + \|b_j\|_2), \quad j = 1, \cdots, s,
\]

(4.7)

where \( \| \cdot \|_i \) means piecewise \( H^i \)-norm (\( i = 1, 2 \)). Thus, (4.7) together with (2.5, 2.6, and 4.6) complete the proof.

**Theorem 4.2.** If \((u, p) \in (H^1_0(\Omega) \cap H^4(\Omega))^2 \times (L^2_0(\Omega) \cap H^2(\Omega)) \) is the exact solution of (1.1), then there exist \( a_j \in (H^1_0(\Omega) \cap H^2(\Omega \setminus \Gamma))^2(j = 1, \cdots, s) \) such that

\[
I_{3h} u_h - u = \sum_{j=1}^s a_{j,h} h_j^2 + O(h^4), \text{ in } L^2(\Omega \setminus \Gamma).
\]

(4.8)

**Proof.** Let \( a_j, b_j, a_{j,h}, b_{j,h} \) satisfy (4.4, 4.5) and set \( \eta = u_h - i_h u - \sum_{j=1}^s a_{j,h} h_j^2 \) as well as \( \xi = p_h - j_h p - \sum_{j=1}^s b_{j,h} h_j^2 \), then there exists \( (w, \varphi) \in (H^1_0(\Omega) \cap H^2(\Omega))^2 \times (L^2_0(\Omega) \cap H^1(\Omega)) \) satisfying

\[
\begin{align*}
\begin{cases}
  B(w, \varphi; v, q) = (\eta, v), \quad \forall (v, q) \in (H^1_0(\Omega))^2 \times L^2_0(\Omega), \\
  \|w\|_2 + \|\varphi\|_1 \leq c\|\eta\|_0.
\end{cases}
\end{align*}
\]

(4.9)

Thus

\[
\|\eta\|_0^2 = B(w, \varphi; \eta, \xi)
\]

\[
= B(w - i_h w, \varphi - j_h \varphi; \eta, \xi) + B(\eta, \xi; i_h w, - j_h \varphi).
\]

(4.10)

From Theorem 3.1, Theorem 3.2, (4.6, 4.9), we have

\[
| B(w - i_h w, \varphi - j_h \varphi; \eta, \xi) | \leq ch(\|w\|_2 + \|\varphi\|_1)(\|\eta\|_1 + \|\xi\|_0)
\]

\[
\leq ch^4\|\eta\|_0
\]

(4.11)

and

\[
| B(\eta, \xi; i_h w, - j_h \varphi) | \leq ch^4(h^{-1}\|w - i_h w\|_1 + \|w\|_2)
\]

\[
\leq ch^4\|w\|_2
\]

\[
\leq ch^4\|\eta\|_0.
\]

(4.12)

Combining (2.5, 4.10, 4.11) and (4.12), we achieve the proof.
5. Remarks

Only the multi-parameter error resolution for the Bernardi-Raugel finite element spaces has been discussed above. In fact, the error resolution arguments presented in this paper can be applied to other pairs of finite element spaces with similar results, for instance, the filtered bilinear-constant finite element spaces. Moreover, if the Green-function technique as in [6] is adapted, then maximum norm estimates can also be obtained.

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References