POINTWISE ERROR ESTIMATES FOR DISCONTINUOUS GALERKIN METHODS WITH LIFTING OPERATORS FOR ELLIPTIC PROBLEMS

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Abstract. In this article, we prove some weighted pointwise estimates for three discontinuous Galerkin methods with lifting operators appearing in their corresponding bilinear forms. We consider a Dirichlet problem with a general second-order elliptic operator.

1. Introduction

Discontinuous Galerkin (DG) methods for elliptic problems have received considerable attention in the last few years. A unified analysis of $L_2$-based global estimates was given by Arnold et. al. [2] for nine DG methods. In that article, in order to do the unified analysis, they cast all the methods in their primal forms (although some methods are more natural in their mixed forms). Four of the methods were shown to be consistent, to be adjoint consistent and to have coercive bilinear forms for the Laplacian. With these properties, they were able to show optimal convergence rates for the gradient and function values. For these four methods, a natural question arises: How do these methods behave pointwise? Kanschat and Rannacher [8] gave a quasi-optimal convergence result in $L_\infty$ for the interior penalty (IP) method, and Chen and Chen [6] gave weighted pointwise estimates for the same method, which implies the result in [8]. In this paper, we show weighted pointwise error estimates for the three remaining methods.

One main difference between the IP method and the three methods considered here is that the latter have terms with lifting operators appearing in their bilinear forms. As pointed out in [2], the IP method can be problematic since the penalty parameters must be chosen sufficiently large to make the method stable. The three remaining methods do not have this problem.

Once one has local $H^1$ estimates, weighted pointwise estimates are easily obtained following the pointwise estimates proof of Schatz [12] for the standard continuous Galerkin method or a similar proof in [6] for the IP method. Therefore, our main contribution is to prove local $H^1$ estimates for these methods. The local $H^1$ analysis becomes more difficult because of the presence of lifting operators. Here we define one of the lifting operators. Let $e$ be the edge shared by triangles $T_1$ and

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and by bounding the bilinear forms. In Section 3, we prove local results. We end the preliminaries by proving some estimates for lifting operators bilinear forms. Then, in Section 2.4 we develop some important approximation results. We end the preliminaries by proving some estimates for lifting operators and by bounding the bilinear forms. In Section 3, we prove local $H^1$ estimates. Finally, in Section 4, we state our pointwise estimates.

Here $M$ is a symmetric, uniformly positive definite matrix, $(\cdot)$ is the average operator across $e$ and $V_h$ denotes our subspace of discontinuous functions. One of the difficulties that we overcame is determining proper bounds for terms of the form $\|\omega r_{M,e}(u_h) - r(u_h)\|_{L_2(T_1 \cup T_2)}$, where $\omega$ is a cut-off function and $[u_h]$ denotes the jump of our approximation across the edge $e$. In order to do this, we use $L_2$-type projection operators and a modification of super-approximation (see Lemmas 2.2 and 2.3).

Chen [6] proved some local $H^1$ error estimates for the local discontinuous Galerkin (LDG) method in its mixed formulation. In this paper, we do the analysis for the LDG method in its primal form, and we repeat the analysis for two other methods. Lifting operators do not appear in the mixed formulation for the LDG method. Therefore, using the mixed formulation avoids the difficulties of analyzing lifting operators. However, one cannot avoid these difficulties in the remaining two methods, because lifting operators also appear in their mixed formulations.

The pointwise estimates obtained here and in [6] are modeled on the pointwise estimates obtained for the standard continuous Galerkin method in [12]. Let $V_h$ be the space of discontinuous functions such that the restriction of a function to an element is a polynomial of degree $r - 1$. The pointwise estimates take on the following forms (compare to Theorems 2.1, 3.1 in [12] and Theorems 5.1, 5.2 in [6]):

\begin{equation}
|\langle u - u_h \rangle(x)| \leq C h \inf_{\tilde{\chi} \in \mathcal{V}_h} \|u - \tilde{\chi}\|_{W^{1,\infty}(\Omega),x,s}, \quad 0 \leq s < r - 2
\end{equation}

and

\begin{equation}
|\nabla_h (u - u_h)(x)| \leq C \inf_{\tilde{\chi} \in \mathcal{V}_h} \|u - \tilde{\chi}\|_{W^{1,\infty}(\Omega),x,s}, \quad 0 \leq s < r - 1.
\end{equation}

Here, $\nabla_h \phi$ denotes the piecewise defined function such that $\nabla_h \phi = \nabla \phi$ on each element of the triangulation. The weighted norm appearing on the right-hand sides of (1.1), (1.2) are precisely defined in Section 2.3, and it will be clear that we can bound that norm by the weighted norm defined in [12] if $\chi$ is continuous. More precisely, $\|u - \chi\|_{W^{1,\infty}(\Omega),x,s} \leq C (\|\sigma_x^s(u - \chi)\|_{L_\infty(\Omega)} + \|\sigma_x^s \nabla(u - \chi)\|_{L_\infty(\Omega)})$, where $\sigma_x(y) = h/(|x - y| + h)$. Therefore, if $s = 0$ (no weight) we get estimates in the $L_\infty$-norm. However, if $s > 0$ our error will be localized around $x$. Consequently, we can also show expansion inequalities (1.2) for these DG methods. The inequalities (1.1), (1.2) will hold if $s = r - 2$ and $s = r - 1$, respectively, as long as we add a logarithmic factor to the right-hand side of the inequalities (see Theorems 3.1, 3.2).

The rest of this paper is organized as follows: In the next section, we present some preliminaries. We define the problem in a precise way, and we introduce our bilinear forms. Then, in Section 2.4 we develop some important approximation results. We end the preliminaries by proving some estimates for lifting operators and by bounding the bilinear forms. In Section 3, we prove local $H^1$ estimates. Finally, in Section 4, we state our pointwise estimates.
2. Preliminaries

2.1. Dirichlet problem. Let \( \Omega \subset \mathbb{R}^2 \) be bounded with smooth boundary. We consider the following Dirichlet problem:

\[
Lu \equiv -\nabla \cdot (A(x)\nabla u) + b(x) \cdot \nabla u + c(x)u = f \quad \text{in } \Omega, \\
u = 0 \quad \text{on } \partial \Omega.
\]

(2.1)

The components of \( A = (a_{ij})_{1 \leq i,j \leq 2} \), \( b = (b_i)_{1 \leq i \leq 2} \) and \( c \) are assumed to be smooth and bounded. Furthermore, we assume that \( A \) is symmetric and uniformly positive definite in \( \Omega \). That is, there exists a constant \( C_{\text{ell}} > 0 \) such that

\[
\psi^T A(x) \psi \geq C_{\text{ell}} |\psi|^2, \quad \forall \ x \in \Omega \text{ and } \psi \in \mathbb{R}^2.
\]

We assume that (2.1) has a unique solution in \( H^1_0(\Omega) \) for all \( f \in L^2(\Omega) \).

In this paper we are not going to trace the dependence of constants on the ellipticity factor \( C_{\text{ell}} \) and upper bounds for \( A(x) \), \( b(x) \) or \( c(x) \).

2.2. Discontinuous approximating spaces and bilinear forms. Suppose we have a family of triangulations \( \mathcal{T}_h \) (possibly with hanging nodes) that fit \( \Omega \) exactly, where \( \Omega = \bigcup_{T \in \mathcal{T}_h} T \). Let \( h = \sup_{T \in \mathcal{T}_h} h_T \), where \( h_T = \text{diam}(T) \). Let \( V_{h,p} \) denote the finite-dimensional space of functions that are polynomials of degree at most \( p \) on each element, and define \( \Sigma_{h,p} = V_{h,p} \times V_{h,p} \). From now on, we set \( V_h = V_{h, r-1} \) and \( \Sigma_h = \Sigma_{h,r-1} \). We naturally define the collection of interior edges as \( \mathcal{E}^0_h = \{\partial T \cap \partial T' : T, T' \in \mathcal{T}_h, T \neq T', \text{meas}_1(\partial T \cap \partial T') \neq 0\} \) and the collection of boundary edges, in general curved, as \( \mathcal{E}^b_h = \{\partial T \cap \partial \Omega : T \in \mathcal{T}_h, \text{meas}_1(\partial T \cap \partial \Omega) \neq 0\} \). The collection of all edges will be denoted by \( \mathcal{E}_h = \mathcal{E}^0_h \cup \mathcal{E}^b_h \). \( S_e \) will denote the union of elements that have \( e \) as an edge. We assume that our elements are non-degenerate; that is, there exists a constant \( C_{\text{nd}}>0 \), independent of \( T \), such that \( h_T \leq C_{\text{nd}} \text{diam}(B_T) \), where \( B_T \) is the largest ball contained in \( T \). Furthermore, we assume the existence of a constant \( C_E > 0 \), independent of \( h \) and \( e \), with \( h \leq C_E h_e \), where \( h_e = \text{length}(e) \). This is the quasi-uniform condition that was used in [6].

We say that \( T \) and \( T' \) are neighbors if \( \partial T \cap \partial T' \in \mathcal{E}^b_h \). From the quasi-uniform condition, it follows that there exists a positive integer \( K \) independent of \( h \) such that each \( T \in \mathcal{T}_h \) has at most \( K \) neighbors (if our meshes do not have hanging nodes, then \( K \) can be 3).

On each edge, as in [2], we define the average and jump operators as follows for \( e \in \mathcal{E}^0_h \):

\[
\langle q \rangle = \frac{1}{2} (q_1 + q_2), \quad [q] = q_1 \cdot n_1 + q_2 \cdot n_2, \\
\langle \phi \rangle = \frac{1}{2} (\phi_1 + \phi_2), \quad [\phi] = \phi_1 n_1 + \phi_2 n_2,
\]

for \( q \) vector valued and \( \phi \) scalar valued. Here \( S_e = T_1 \cup T_2 \), \( q_i = q|_{T_i} \), \( \phi_i = \phi|_{T_i} \), and \( n_i \) is the exterior normal to \( T_i \), \( i = 1, 2 \). For \( e \in \mathcal{E}^b_h \),

\[
\langle q \rangle = q, \quad [\phi] = \phi n,
\]

where \( n \) is the outward unit normal. Note that \([q]\) is a scalar and \([\phi]\) a vector. The quantities \([q]\) and \(\langle \phi \rangle\) on boundary edges are not required, so they are left undefined.
Now we present some local lifting operators as in [2]. Let $M$ be a symmetric, smooth, bounded and uniformly positive definite matrix in $\Omega$. Let $r_{M,e} : [L^2(e)]^2 \to \Sigma_h$ and $l_{M,e} : L^2(e) \to \Sigma_h$ be given by

\[
\begin{aligned}
\int_{S_e} r_{M,e}(q)M \tau dx &= -\int_{e} q^T (M \tau) ds, \\
\int_{S_e} l_{M,e}(\phi)M \tau dx &= -\int_{e} \phi[M\tau]ds, \quad \forall \tau \in \Sigma_h.
\end{aligned}
\]

We set the global lifting operators to be $r_M(q) = \sum_{e \in \mathcal{E}_h} r_{M,e}(q)$ and $l_M(\phi) = \sum_{e \in \mathcal{E}_h} l_{M,e}(\phi)$.

Now, we are ready to define the bilinear forms. They are the modified BRMPS [3], modified BMMPR [4] and local discontinuous Galerkin bilinear forms. (See [2] for the bilinear forms for the Laplacian.) The following term is common to all three:

\[
\theta(u, v) = \sum_{T \in \mathcal{T}_h} \int_T (\nabla u^T A \nabla v + (b^T \nabla u)v + cuv)dx - \sum_{e \in \mathcal{E}_h} \int_{S_e} (\langle A \nabla_h u \rangle [v] + \langle A \nabla_h v \rangle [u] + b^T [u] \langle v \rangle)ds.
\]

**Modified BRMPS**

\[
B(u, v) = \theta(u, v) + \sum_{e \in \mathcal{E}_h} \eta_e \int_{S_e} r_{A,e}([u])^T A r_{A,e}([v])dx + \frac{1}{h_e} \int_{e} [u][v]ds.
\]

**Modified BMMPR**

\[
B(u, v) = \theta(u, v) + \int_{\Omega} r_{A}([u])^T A r_{A}([v])dx + \sum_{e \in \mathcal{E}_h} \eta_e \int_{S_e} r_{l,e}([u])^T r_{l,e}([v])dx + \frac{1}{h_e} \int_{e} [u][v]ds.
\]

**Local Discontinuous Galerkin**

\[
B(u, v) = \theta(u, v) + \int_{\Omega} (r_{A}([u]) + l_{A}(\beta^T [u]))^T A (r_{A}([v]) + l_{A}(\beta^T [v]))dx - \sum_{e \in \mathcal{E}_h} \int_{e} (\langle A \nabla_h u \rangle \beta^T [v] + \beta^T [u] \langle A \nabla_h v \rangle)ds + \sum_{e \in \mathcal{E}_h} \frac{\eta_e}{h_e} \int_{e} [u][v]ds.
\]

Here $\eta_e$ is constant for each $e$, and is bounded for all $e$. If we let $\eta = \inf_{e} \eta_e$, then we require that $K < \eta$ (See Section 2.2 for the definition of $K$) for the Modified Bassi form and $0 < \eta$ for the two remaining forms. Also, $\beta$ is a constant vector on each interior edge and is bounded component-wise for all $e$. Our modification of the first two methods is solely motivated by our analysis. It consists of adding the last terms over the boundary edges. Without this modification we were not able to prove Theorem 3.1 since we were unable to show (2.19) for curved edges. Whether this modification is necessary in practice we do not know. We intend to investigate this question in the future.

The discontinuous approximation $u_h$ solves

\[
B(u_h, v) = (f, v), \quad \forall v \in V_h.
\]

For each method we use the corresponding bilinear form.
2.3. Discontinuous Sobolev norms. If $D \subset \Omega$, we define our discontinuous Sobolev space as in [6]:

$$W^{1,p}_h(D) = \{ v : v \in W^{1,p}(T \cap D), \forall \ T \in T_h \}.$$ 

This space is equipped with the norm ($1 \leq p < \infty$)

$$||v||_{W^{1,p}_h(D)} = \left( \sum_{j=0}^{l} ||v||^p_{W^{1,p}_h(T_j)} \right)^{\frac{1}{p}}, \quad ||v||_{W^{1,p}_h(T)} = \left( \sum_{T \in T_h} ||v||^p_{W^{1,p}(T \cap D)} \right)^{\frac{1}{p}},$$

with the appropriate modification for $p = \infty$. When $p = 2$, we set $H^1_h(D) = W^{1,2}_h(D)$.

Let $D \subset \Omega$ and $1 \leq p < \infty$. The norms that occur in most of our analysis take on the following form:

$$||v||^p_{W^{1,p}_h(D)} = ||v||^p_{W^{1,p}_h(D)} + \sum_{e \in E_h} h_e^{-1-p}||v||^p_{L_p(e)} + \sum_{s \in E_h^s} h_e^{1-p}||v||^p_{L_p(e)}.$$

For $p = \infty$,

$$||v||^p_{W^{1,\infty}_h(D)} = ||v||^p_{W^{1,\infty}_h(D)} + \sup_{e \in E_h} \frac{1}{h_e} ||v||_{L_\infty(e)} + \sup_{e \in E_h^s} ||v||_{L_\infty(e)}.$$

We consider the weight $\sigma^s_x(y) = \left( \frac{h}{|x-y|+h} \right)^s$ as in [12]. If we let

$$||v||^p_{W^{1,p}_h(\Omega),x,s} = ||\sigma^s_x v||^p_{L_p(\Omega)} + ||\sigma^s_x \nabla v||^p_{L_p(\Omega)}$$

for $1 \leq p < \infty$, then for fixed $x$ we define the norms

$$||v||^p_{W^{1,p}_h(\Omega),x,s} = ||v||^p_{W^{1,p}_h(\Omega),x,s} + \sum_{e \in E_h} h_e^{-1-p}||v||^p_{L_p(e)} + \sum_{s \in E_h^s} h_e^{1-p}||v||^p_{L_p(e)},$$

again with the appropriate modification for $p = \infty$.

2.4. Approximation. We start by stating well-known trace inequalities. Let $\phi$ be an edge of $T \in T_h$ and $\phi$ be either a scalar- or vector-valued function. Then, for $1 \leq p \leq \infty$, we have

$$||\phi||_{L_p(e)} \leq C_h\phi||L_p(T) + h^{1-\frac{1}{p}}||\phi||_{W^{1,p}(T)}.$$  

If we restrict $\phi$ to $V_{h,i}$ or $\Sigma_{h,i}$, for some fixed $i > 0$, we can state some inverse inequalities that are also well known:

$$||\phi||_{W^{1,1}(T)} \leq C h^{1-\frac{1}{2}}||\phi||_{W^{1,1}(T)}$$

and

$$||\phi||_{L_p(e)} \leq C h^{1-\frac{1}{p}}||\phi||_{L_p(T)}.$$  

where $C$ does not depend on $\phi, h, e,$ or $T$.

The following is a standard elementwise approximation result. Let

$$v \in W^{1,p}_h(\Omega)([W^{1,p}_h(\Omega)]^2)$$

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with \(0 \leq i \leq j \leq r\). Then, there exists a \(\phi \in V_h(\Sigma_h)\) with
\[
\|v - \phi\|_{W^{1,p}(T)} \leq C h^{j-i} |v|_{W^{1,p}(T)}, \quad \forall T \in T_h,
\]
where \(C\) does not depend on \(v, h,\) or \(T\).

We present some function spaces, as in [3], that will help us in stating further approximation results. If \(S \subset R \subset \Omega\), let \(\partial \subset (S, R) = \text{dist}(\partial S \setminus \partial \Omega, \partial R \setminus \partial \Omega)\). The spaces are defined as follows:
\[
V_h^\subset(A) = \{v \in V_h : \partial \subset (\supp(v), A) > 0\},
\]
and
\[
C^\subset(A) = \{v \in C^\subset : \partial \subset (\supp(v), A) > 0\}.
\]
The following lemma follows from trace inequalities and elementwise approximation. (See section 4.3 in [2] for a similar result.)

**Lemma 2.1.** Let \(D_0 \subset D_d\) with \(\partial \subset (D_0, D_d) = d \geq \kappa h\) (for a fixed \(\kappa > 1\) sufficiently large). Let \(v \in H^1_h(D_d)\). Then, there exists \(\psi \in V_h\) such that
\[
|||v - \psi|||_{H^1_h(D_0)} \leq C h^{r-1} |v|_{H^1_h(D_d)},
\]
where \(C\) is independent of \(v, h, D_0\) and \(D_d\). Furthermore, if \(\supp(v) \subset D_0\), then \(\psi \in V_h^\subset(D_d)\).

Throughout this paper, we are going to be estimating functions of the form \(v = \omega \chi\) or \(v = \omega^2 \chi\), where \(\chi \in V_h\) or \(\Sigma_h\) and \(\omega\) is a cut-off function. Hence, we develop some approximation results for these functions.

**Lemma 2.2.** Let \(\chi \in V_h\), and let \(\omega\) be a smooth function. Suppose there exist constants \(C > 0\) and \(d \geq \kappa h\) for some constant \(\kappa > 1\) such that \(|\omega|_{W^{l,\infty}(\Omega)} \leq Cd^{-l}\) for \(l = 0, 1, \ldots, r + 1\). Then,
\[
|\omega^2 \chi|_{H^r(T)} \leq C \frac{1}{h^{r-2}} (d^{-1} |\omega \chi|_{H^1(T)} + d^{-2} ||\chi||_{L^2(T)}),
\]
\[
|\omega^2 \chi|_{H^r(T)} \leq C \frac{1}{h^{r-2}} (d^{-1} |\omega \chi|_{L^2(T)} + d^{-2} ||\chi||_{L^2(T)}),
\]
\[
|\omega \nabla (\omega \chi)|_{H^r(T)} \leq C \frac{1}{h^{r-1}} (d^{-1} ||\nabla (\omega \chi)||_{L^2(T)} + d^{-2} ||\chi||_{L^2(T)}),
\]
\[
|\omega \chi|_{H^k(T)} \leq C \frac{1}{h^{k-2}} (d^{-1} |\omega \chi|_{H^1(T)} + d^{-2} ||\chi||_{L^2(T)}) \quad \text{for } k = 1, \ldots, r - 1,
\]
and
\[
|\omega \chi|_{H^r(T)} \leq C \frac{1}{h^{r-1}} d^{-1} ||\chi||_{L^2(T)}.
\]
Here \(C\) is independent of \(\omega, \chi, T,\) and \(h\).

**Proof.** By Leibniz’s rule, the fact that the \(r\)th derivatives of \(\chi\) vanish in \(T\) and inverse estimates, we get that
\[
|\omega^2 \chi|_{H^r(T)} \leq C (\sum_{l=2}^{r} h^{l-r} |\omega^2|_{W^{l,\infty}(T)}) ||\chi||_{L^2(T)} + \sum_{|\alpha|=1, \beta=r-1} ||D^\alpha \omega^2 D^\beta \chi||_{L^2(T)}).
\]

By the decay properties of \(\omega\) and the fact that \(hd^{-1} \leq 1\), we see that
\[
(\sum_{l=2}^{r} h^{l-r} |\omega^2|_{W^{l,\infty}(T)}) ||\chi||_{L^2(T)} \leq Cd^{-2} h^{2-r} ||\chi||_{L^2(T)}.
\]
Now we handle the second sum in (2.13). Note that $D^\alpha \omega^2 = 2 \omega D^\alpha \omega$ since $|\alpha| = 1$. Therefore,

$$\sum_{|\alpha|=1,|\beta|=r-1} ||D^\alpha \omega^2 D^\beta \chi||_{L^2(T)} \leq C d^{-1} \sum_{|\beta|=r-1} ||\omega D^\beta \chi||_{L^2(T)}.$$

Now we let $\hat{\omega} = \frac{1}{|T|} \int_T \omega \, dx$. By the triangle inequality, we have that

$$||\omega D^\beta \chi||_{L^2(T)} \leq ||(\omega - \hat{\omega}) D^\beta \chi||_{L^2(T)} + ||\hat{\omega} D^\beta \chi||_{L^2(T)}.$$

Using approximation properties, we see that

$$||(\omega - \hat{\omega}) D^\beta \chi||_{L^2(T)} \leq C h |\omega|_{W^{1,\infty}(T)} ||D^\beta \chi||_{L^2(T)}.$$

Using inverse estimates and decay properties of $\omega$, we have

$$||(\omega - \hat{\omega}) D^\beta \chi||_{L^2(T)} \leq C d^{-1} h^{2-r} ||\chi||_{L^2(T)}.$$

To handle the next term we again use an inverse estimate to get

$$||\hat{\omega} D^\beta \chi||_{L^2(T)} \leq C h^{2-r} ||\hat{\omega} \chi||_{H^1(T)}.$$

Using the triangle inequality, we have

$$||\hat{\omega} \chi||_{H^1(T)} \leq ||(\hat{\omega} - \omega) \chi||_{H^1(T)} + ||\omega \chi||_{H^1(T)}.$$

By using the product rule, approximation properties, and inverse estimates, we obtain

$$||(\hat{\omega} - \omega) \chi||_{H^1(T)} \leq C d^{-1} ||\chi||_{L^2(T)}.$$

Combining these estimates, we have that

$$\sum_{|\alpha|=1,|\beta|=r-1} ||D^\alpha \omega^2 D^\beta \chi||_{L^2(T)} \leq d^{-1} h^{2-r} ||\omega \chi||_{H^1(T)} + d^{-2} h^{2-r} ||\chi||_{L^2(T)}.$$

This proves (2.8). By again introducing $\hat{\omega}$ we can bound $||\omega \chi||_{H^1(T)}$ by the right-hand side of (2.9). This will prove (2.9). By using the triangle inequality we see that

$$||\omega \nabla (\omega \chi)||_{H^1(T)} \leq ||\omega^2 \nabla (\chi)||_{H^1(T)} + ||\omega \nabla \omega||_{H^1(T)}.$$

We can then use (2.9) to bound $||\omega^2 \nabla (\chi)||_{H^1(T)}$ by the right-hand side of (2.10), and we can use Leibniz’s rule and inverse estimates to bound $||\omega \nabla \omega||_{H^1(T)}$. This would prove (2.10). By Leibniz’s rule, inverse estimates and using the decay properties of $\omega$, we can prove (2.10) and (2.12). We omit the proofs. □

Now we can state a super-approximation result similar to that in [12]. The differences between this approximation result and the one contained in [12] is that $\omega$ appears on the right-hand side of our result. This will allow us to perform “kick back” arguments. (See the proof of Theorem 3.1.)

**Lemma 2.3.** Let $\partial_\zeta(D_0, D_d) = d > \kappa h$, where $\omega \in C^\infty_v(D_0)$. Suppose

$$||\omega||_{W^{1,\infty}(D_0)} \leq C d^{-1}$$

for $l = 0, 1, \ldots, r + 1$. Then, for all $\chi \in V_h$ there exists $\psi \in V^<_h(D_d)$ with

$$||\omega^2 \chi - \psi||_{H^1_0(T)} \leq C h (d^{-1} ||\omega \chi||_{H^1_0(D_d)} + d^{-2} ||\chi||_{L^2(D_d)}),$$

where $C$ is independent of $\chi$ and $\omega$.

**Proof.** This easily follows from Lemma 2.1 and (2.8). □
2.5. **Boundedness and consistency of the forms.** We start by defining and stating some properties of certain projection operators that we use throughout this paper. In this direction, let $M$ be a symmetric, smooth, bounded matrix that is uniformly positive definite in $\Omega$. If $g \in L_2(\Omega)$, we define $P_M(g) \in \Sigma_h$ by the following equation:

\[(2.14) \quad \int_\Omega \chi^T M g = \int_\Omega \chi^T M P_M(g), \quad \forall \chi \in \Sigma_h.\]

Note that $P_M$ can be defined elementwise since $\Sigma_h$ is a space of discontinuous functions. If $M = I$, then this will simply be the vector-valued $L_2$-projection operator. $L_2$-projection operators have been analyzed extensively. The proof of the following lemma, which we omit, follows the proof for the $L_2$-projection operator ([7]); however, it is much simpler since $V_h$ consists of discontinuous functions.

**Lemma 2.4.** Let $M$ be a symmetric, smooth and bounded matrix that is uniformly positive definite. Let $P_M$ be defined by (2.14) and $1 \leq p \leq \infty$. Then, for all $T \in T_h$, \[\|P_M(g)\|_{L_p(T)} \leq C_1 \|g\|_{L_p(T)}\]

and \[\|g - P_M(g)\|_{H^k(T)} \leq C_2 h^{-k} \|g\|_{H^k(T)} \quad \text{for} \quad k = 1, \ldots, r,\]

where $C_1$ and $C_2$ are independent of $g$ and $T$.

In order to show boundedness of our forms, we need some estimates for our lifting operators. The following lemma is an extension of Lemma 2(ii) in [4].

**Lemma 2.5.** Let $M$ be smooth, bounded, and uniformly positive definite in $\Omega$. Let $1 \leq p, q \leq \infty$, $\frac{1}{p} + \frac{1}{q} = 1$. Then, there exists a constant $C$ such that for all $\phi \in [L_p(e_1)]^2$ and $\chi \in [L_q(e_2)]^2$,

\[(2.15) \quad \int_{S_{e_1} \cap S_{e_2}} r_{M,e_1}(\phi)^T M r_{M,e_2}(\chi) dx + \int_{S_{e_1} \cap S_{e_2}} l_{M,e_1}(\phi)^T M l_{M,e_2}(\chi) dx \]

\[\leq C \frac{1}{h} \|\phi\|_{L_p(e_1)} \|\chi\|_{L_q(e_2)} \]

In the case that $e_1$ and $e_2$ do not belong to the same triangle, the left-hand side of (2.15) will be zero.

**Proof.** The last statement of the lemma follows by the definition of the lifting operators. In the other case, by the boundedness of $M$ and (2.5), we have

\[\int_{S_{e_1} \cap S_{e_2}} r_{M,e_1}(\phi)^T M r_{M,e_2}(\chi) dx = \int_{e_1} \phi^T M \langle r_{M,e_2}(\chi) \rangle ds \]

\[\leq C \|\phi\|_{L_p(e_1)} \|\langle r_{M,e_2}(\chi) \rangle\|_{L_q(e_1)} \]

\[\leq C h^{-\frac{1}{p}} \|\phi\|_{L_p(e_1)} \|r_{M,e_2}(\chi)\|_{L_q(e_2)}.\]

Now we use a duality argument to bound $\|r_{M,e_2}(\chi)\|_{L_q(e_2)}$. If $g = M^{-1}z$, then

\[\int_{S_{e_2}} r_{M,e_2}(\chi)^T z dx = -\int_{e_2} \chi^T M (P_M(g)) ds.\]
By Hölder’s inequality, (2.25), and Lemma 2.4 we easily get
\[- \int_{e_2} \chi^T M \langle P_M (g) \rangle \, ds \leq C h^{-\frac{1}{2}} \| \chi \| L_q (e_2) \| g \| L_p (S_{e_2}).\]

Therefore, by duality \( \| r_{M, e_2} (\chi) \|_{L_q (S_{e_2})} \leq C h^{-\frac{1}{2}} \| \chi \|_{L_q (e_2)} \) since \( \| g \|_{L_p (S_{e_2})} \leq C \| z \|_{L_p (S_{e_2})}. \) Hence, we have established the following:

\[
(2.16) \quad \int_{S_{e_1} \cap S_{e_2}} r_{M, e_1} (\phi)^T M r_{M, e_2} (\chi) \, dx \leq C \frac{1}{h} \| \phi \|_{L_p (e_1)} \| \chi \|_{L_q (e_2)}.
\]

The last two terms can be bounded following similar steps. □

In the case that \( e_1 \) and \( e_2 \) belong to a common triangle, a simple exercise shows
\[\max_{y \in e_1} (\sigma^e_2 (y)) \leq 2^s \min_{y \in e_2} (\sigma^e_2 (y)).\]Therefore,

\[
(2.17) \quad \frac{1}{h} \| \phi \|_{L_p (e_1)} \| \chi \|_{L_q (e_2)} \leq C \frac{1}{h} \| \sigma^e_2 \phi \|_{L_p (e_1)} \| \sigma^e_2 \chi \|_{L_q (e_2)}.
\]

If we take into account that \( r_M = \sum_{e \in E_h} l_{M, e} \) and \( l_M = \sum_{e \in E_h} l_{M, e} \), make use of Hölder’s inequality (both for the integrals and summation), and apply Lemma 2.5 and (2.17), we can show the following boundedness of our forms. (See [6], [2] for analogous results.)

**Lemma 2.6.** Let \( 1 \leq p, q \leq \infty, \frac{1}{p} + \frac{1}{q} = 1 \). For all three forms, there exists a positive constant \( C \) such that for all \( u \in W^{1, p}_h (\Omega) \) and \( v \in W^{1, q}_h (\Omega) \)

\[
(2.18) \quad \| B (v, u) \| + \| B (u, v) \| \leq C \| u \|_{W^{1, p}_h (\Omega), x, u} \| v \|_{W^{1, q}_h (\Omega), x, -s},
\]

where \( C \) is independent of \( x, u \) and \( v \).

The next important inequality is an extension of Lemma 2(i) in [3].

**Lemma 2.7.** Let \( M \) be given as in Lemma 2.5. Let \( e \in E^0_h \), \( \phi \in [P_{r-1} (e)]^2 \) and suppose \( \omega \in C^\infty (\Omega) \). Then,

\[
(2.19) \quad h^{-1}_e \int_e (\omega \phi)^T M (\omega \phi) \, ds \leq C \int_{S_e} \omega^2 r_{M, e} (\phi)^T M r_{M, e} (\phi) \, dx + h_e \| \omega \|_{W^{1, \infty} (S_e)}^2 \| \phi \|_{L_2 (e)}^2.
\]

**Proof.** Let \( v \in [P_p (e)]^2 \) for some fixed \( p \). Then, \( v \) is defined naturally on the line containing \( e \), call it \( l \). As in [3], we define \( \overline{v} \in [P_p (R^2)]^2 \) as the vector-valued polynomial satisfying \( v = \overline{v} \) on \( l \) and which is constant on the lines perpendicular to \( l \). As pointed out in [3],

\[
(2.20) \quad \| \overline{v} \|_{L_2 (S_e)} \leq Ch \| v \|_{L_2 (e)}.
\]

Also, let \( \bar{\omega} \equiv \min_{S_e} \omega \). It follows by the mean value theorem, possibly applying it twice, that

\[
(2.21) \quad \| \bar{\omega} - \omega \|_{L_\infty (S_e)} \leq Ch \| \omega \|_{W^{1, \infty} (S_e)}.
\]

We easily see by our definitions that

\[
(2.22) \quad \int_e (\omega \phi)^T M (\omega \phi) \, ds = E_1 + E_2,
\]
where

\[
E_1 = h^{-1}_e \int_e (\omega \phi^T M(\omega \phi) - (\tilde{\omega} \phi)^T \tilde{M}(\tilde{\omega} \phi)) ds,
\]

\[
E_2 = -h^{-1}_e \omega^2 \int_{S_e} (\phi^T M_{e,e}(\phi)) ds.
\]

We rewrite \(E_1\) as

\[
E_1 = Ch^{-1}_e \int_e (\omega - \tilde{\omega})(\omega + \tilde{\omega})\phi^T M\phi ds.
\]

By the Cauchy-Schwarz inequality and the arithmetic-geometric mean inequality we have

\[
E_1 \leq Ch^{-1}_e \int_e (\omega - \tilde{\omega})^2 \phi^T M\phi ds + ch^{-1}_e \int_e (\omega + \tilde{\omega})^2 \phi^T M\phi ds.
\]

Later we will choose \(\epsilon > 0\) sufficiently small. Finally, using (2.21) and \((\omega + \tilde{\omega})^2 \leq 2(\omega^2 + \tilde{\omega}^2) \leq 2\omega^2\), we see that

\[
E_1 \leq Ch^{-1}_e |\omega|_{W^{1,\infty}(S_e)}^2 ||\phi||_{L_2(e)}^2 + 2ch^{-1}_e \int_e \omega^2 \phi^T M\phi ds.
\]

Again, using the Cauchy-Schwarz inequality and the arithmetic-geometric mean inequality, we have

\[
E_2 \leq \omega^2 (ch^{-2}_e \int_{S_e} \phi^T M\phi dx + C \int_{S_e} \omega^2 r_{M,e}(\phi)^T M_{e,e}(\phi) dx).
\]

By using (2.20) and the positive definiteness of \(M\), we see that

\[
E_2 \leq C_1 \epsilon \int_e \omega^2 \phi^T M\phi ds + C \int_{S_e} \omega^2 r_{M,e}(\phi)^T M_{e,e}(\phi) dx,
\]

where \(C_1\) is a constant independent of \(\epsilon\).

Finally, taking \(\epsilon\) small enough, we arrive at our conclusion. \(\square\)

The next lemma can easily be shown by applying integration by parts (see Section 3.3 in [2] for similar results).

**Lemma 2.8.** For all the forms we have consistency and adjoint consistency. That is, if \(Lu = f\) or \(L^*w = f\), with \(u, w \in H^1_0(\Omega)\), then

\[
(2.23) \quad B(u, v) = (f, v) \quad \text{or} \quad B(v, w) = (f, v), \quad \forall v \in V_h.
\]

Until now, we have not addressed if (2.2) is well defined. Coerciveness, of course, will not hold for a general second-order elliptic operator. However, using techniques similar to those in Section 4.2 of [2], and in addition taking care of the lower-order terms, we can show the following lemma.

**Lemma 2.9.** For all three forms there exists a constant \(C > 0\) such that \(\forall \chi \in V_h\)

\[
(2.24) \quad |||\chi|||_{H^1_h(\Omega)}^2 \leq C(B(\chi, \chi) + ||\chi||_{L_2(\Omega)}^2).
\]

If we use this fact, Lemma 2.8 and use the techniques in [10], we could show that our problem is well defined for sufficiently small \(h\).
3. Local $H^1$ estimates

We start with our main theorem.

**Theorem 3.1.** Let $D_0 \subset \Omega$ with $\partial(D_0, D_d) = d > \kappa h$ (where $\kappa > 1$ is a sufficiently large fixed constant). Suppose $u$ and $u_h \in V_h$ satisfy

$$B(u - u_h, v) = 0, \quad \forall v \in V_h$$

for any of the forms above. Then,

$$|||u - u_h|||_{H^1(D_0)} \leq C \inf_{\chi \in V_h} (|||u - \chi|||_{H^1(D_d)} + d^{-1}|||u - \chi|||_{L^2(D_d)}) + C d^{-1}|||u - u_h|||_{L^2(D_d)},$$

where $C$ is independent of $d$.

**Proof.** Since $u - u_h = (u - \chi) - (u_h - \chi)$, it suffices to show

$$|||u - u_h|||_{H^1(D_0)} \leq C(|||u|||_{H^1(D_d)} + d^{-1}|||u|||_{L^2(D_d)}) + C d^{-1}|||u - u_h|||_{L^2(D_d)}.$$

By the triangle inequality, it will be enough to establish

$$|||u_h|||_{H^1(D_0)} \leq C|||u|||_{H^1(D_d)} + C d^{-1}|||u_h|||_{L^2(D_d)}.$$  

To this end, let $\omega \in C^\infty_0(D_d)$ with $\omega \equiv 1$ on $D_d$ and $|\omega|_{W^{1,\infty}(\Omega)} \leq C d^{-1}$ for $l = 0, 1, \ldots, r + 1$. For a moment, let us assume that we can show the following inequality for all the forms:

$$|||\omega u_h|||^2_{H^1(D_0)} \leq CB(u_h, \omega^2 u_h) + C d^{-2}|||u_h|||^2_{L^2(D_d)}.$$ 

By (3.1), we can write

$$B(u, \omega^2 u_h) = B(u, \omega^2 u_h - \chi) - B(u, \omega^2 u_h - \chi) + B(u, \omega^2 u_h)$$

for any $\chi \in V_h$. Since our forms are bounded, we have

$$B(u, \omega^2 u_h) \leq C|||u|||_{H^1(D_d/2)}|||\omega^2 u_h|||_{H^1(D_d/2)}$$

$$\leq C|||u|||_{H^1(D_d)}(|||\omega u_h|||_{H^1(D_d)} + d^{-1}|||u_h|||_{L^2(D_d)}).$$

Now, applying the arithmetic-geometric mean inequality, we see that

$$B(u, \omega^2 u_h) \leq C|||u|||^2_{H^1(D_d)} + \epsilon|||\omega u_h|||^2_{H^1(D_d)} + C d^{-2}|||u_h|||^2_{L^2(D_d)}.$$ 

Using the boundedness of our forms and Lemma 2.3, we obtain

$$B(u, \omega^2 u_h - \chi) \leq C|||u|||^2_{H^1(D_d)} |||\omega^2 u_h - \chi|||_{H^1(D_d/2)}$$

$$\leq C|||u|||_{H^1(D_d)} (hd^{-1}|||\omega u_h|||_{H^1(D_d)} + hd^{-2}|||u_h|||_{L^2(D_d)}).$$

Taking into account that $hd^{-1} < 1$, and applying the arithmetic-geometric mean inequality, we have

$$B(u, \omega^2 u_h - \chi) \leq C|||u|||^2_{H^1(D_d)} + \epsilon|||\omega u_h|||^2_{H^1(D_d)} + C d^{-2}|||u_h|||^2_{L^2(D_d)}.$$ 

Similarly,

$$B(u, \omega^2 u_h - \chi) \leq C h|||u_h|||_{H^1(D_d/2)}(d^{-1}|||\omega u_h|||_{H^1(D_d)} + d^{-2}|||u_h|||_{L^2(D_d)}).$$ 

Using (2.4) and (2.5), we can show the inverse inequality

$$h|||u_h|||_{H^1(D_d/2)} \leq C|||u_h|||_{L^2(D_d)}.$$ 

Therefore, applying the arithmetic-geometric mean inequality one more time gives

$$|||u_h|||_{H^1(D_d)} \leq C|||u|||^2_{H^1(D_d)} + C d^{-2}|||u_h|||^2_{L^2(D_d)}.$$
Finally, using (3.3), (3.4) and making $\epsilon$ small enough in (3.5), (3.6), and (3.7), we arrive at

$$\|\omega u_h\|_{H^1_0(\Omega)}^2 \leq C(\|u\|_{H^1(D_d)}^2 + d^{-2}\|u_h\|_{L^2(D_d)}^2).$$

This will imply (3.2), which in turn implies our theorem.

We are left to show (3.3). We first prove this for the Modified BRMPS form. First, by applying (2.3) and (2.11), we see that

$$\sum_{e \in E} h_e |\langle \nabla (\omega u_h) \rangle|_{L^2(e)}^2 + \sum_{e \in \partial^h} h_e |\nabla (\omega u_h)|_{L^2(e)}^2 \leq C \sum_{T \in T_h} \int_T \nabla (\omega u_h)^2 dx + C d^{-2}\|u_h\|_{L^2(\Omega)}^2. \tag{3.9}$$

By using (3.9), the positive definiteness of $A$, (2.19) and (2.5), we have

$$\|\omega u_h\|_{H^1_0(\Omega)}^2 \leq C I + C d^{-2}\|u_h\|_{L^2(D_d)}^2, \tag{3.10}$$

where

$$I \equiv \sum_{T \in T_h} \int_T \nabla (\omega u_h)^T A \nabla (\omega u_h) dx + \sum_{e \in \partial^h} \int_{S_e} \omega^2 r_{A,e}(\omega u_h)^T A r_{A,e}(\omega u_h) dx + \sum_{e \in \partial^h} \frac{1}{h_e} \int_e \omega^2 |u_h|^2 ds.$$ 

In the last two inequalities we used the fact that each element has at most $K$ neighbors.

Let

$$G \equiv \sum_{T \in T_h} \int_T \nabla (\omega u_h)^T A \nabla (\omega u_h) dx + 2 \sum_{e \in \partial^h} \int_{S_e} \nabla h (\omega u_h)^T A \omega r_{A,e}(\omega u_h) dx + \sum_{e \in \partial^h} \eta_e \int_{S_e} \omega^2 r_{A,e}(\omega u_h)^T A r_{A,e}(\omega u_h) dx.$$ 

Using the arithmetic-geometric mean inequality on the middle term and the fact that each triangle has at most $K$ neighbors, we get

$$G \geq (1 - \frac{K}{\epsilon_1}) \sum_{T \in T_h} \int_T \nabla (\omega u_h)^T A \nabla (\omega u_h) dx + (\eta - \epsilon_1) \sum_{e \in \partial^h} \int_{S_e} \omega^2 r_{A,e}(\omega u_h)^T A r_{A,e}(\omega u_h) dx.$$ 

Choosing $\epsilon_1$ to satisfy $K < \epsilon_1 < \eta$, we see that

$$I \leq C(G + \sum_{e \in \partial^h} \frac{1}{h_e} \int_e \omega^2 |u_h|^2 ds). \tag{3.11}$$
Using the definition of $G$ and adding and subtracting the terms of $B(u_h, \omega^2 u_h)$ (for the Modified BRMPS form) to the right-hand side of (3.11), we arrive at

\[ I \leq C(B(u_h, \omega^2 u_h)) + \sum_{T \in T_h} \int_T \nabla (u_h)^T A \nabla (u_h) - \nabla (\omega^2 u_h)^T A \nabla u_h \, dx \]

\[ + \sum_{e \in E_h} (2 \int_{S_e} \nabla_h (u_h)^T A r_{A,e}([u_h]) \, ds ) \]

\[ + \int_e \left( \langle \nabla_h (\omega^2 u_h) \rangle^T A [u_h] + \langle \nabla_h u_h \rangle^T A [\omega^2 u_h] \rangle ds \right) \]

\[ + \sum_{e \in E_h} \eta_e \int_{S_e} (\omega^2 r_{A,e}([u_h])^T A r_{A,e}([u_h]) - r_{A,e}([\omega^2 u_h]) A r_{A,e}([u_h])) \, ds \]

\[ - \sum_{T \in T_h} \int_T (c(\omega u_h)^2 + u_h \cdot \nabla (\omega^2 u_h)) \, dx + \sum_{e \in E_h} \int_e u_h \cdot [\omega^2 u_h] \, ds \]

\[ = C(B(u_h, \omega^2 u_h)) + I_1 + I_2 + I_3 + I_4. \]

Note that $I_4$ consists of the lower-order terms of our bilinear form. By applying the product rule to each term of $I_1$, we see that

\[ (3.12) \quad I_1 = \left| \sum_{T \in T_h} \int_T u_h \nabla \omega^T A \nabla \omega \, dx \right| \leq C d^{-2} \| u_h \|_{L^2(D_d)}^2, \]

where we also used that $|\nabla \omega|_{L^\infty(\Omega)} \leq C d^{-1}$ in the last inequality.

For $I_2$, we use the definitions of $P_A$, (2.11) and of our lifting operator $r_{A,e}$, to rewrite it as

\[ I_2 = -\left( \sum_{e \in E_h} \int_e 2 \langle P_A(\omega \nabla_h (u_h)) \rangle^T A [u_h] \, ds \right) \]

\[ - \int_e \left( \langle \nabla_h (\omega^2 u_h) \rangle^T A [u_h] + \langle \nabla_h u_h \rangle^T A [\omega^2 u_h] \rangle ds \right). \]

By the product rule, $\langle \nabla_h (\omega^2 u_h) \rangle = \langle \omega^2 \nabla_h (u_h) + 2 \omega \nabla_h (\omega) u_h \rangle$. Adding a term to this and applying the product one more time, we see that

\[ \langle \nabla_h (\omega^2 u_h) \rangle + \langle \omega^2 \nabla_h (u_h) \rangle = 2 \omega \langle \nabla_h (u_h) \rangle. \]

Therefore, we can express $I_2$ in the following form:

\[ I_2 = -2 \sum_{e \in E_h} \int_e \langle P_A(\omega \nabla_h (u_h)) - \omega \nabla_h (\omega u_h) \rangle^T A [u_h] \, ds \]

By the Cauchy-Schwarz inequality, (2.13) and (2.14),

\[ I_2 \leq C \sum_{e \in E_h} h^{-1/2} \| u_h \|_{L^2(S_e)} (h^{-1/2} \| P_A(\omega \nabla_h (u_h)) \| H^1(S_e)) \]

\[ - \omega \nabla_h (\omega u_h) \|_{L^2(S_e)} + h^{1/2} \| P_A(\omega \nabla_h (\omega u_h)) - \omega \nabla_h (\omega u_h) \| H^1(S_e)). \]

Moreover, by Lemma (2.4) and (2.10),

\[ I_2 \leq C \sum_{e \in E_h} \| u_h \|_{L^2(S_e)} (d^{-1} \| \nabla_h (\omega u_h) \|_{L^2(S_e)} + d^{-2} \| u_h \|_{L^2(S_e)}). \]
Finally, using the positive definiteness of $A$ and the arithmetic-geometric mean inequality, we see that

\begin{equation}
I_2 \leq \epsilon \sum_{T \in T_h} \int_T \nabla (\omega u_h)^T A \nabla (\omega u_h) dx + C d^{-2} \|u_h\|_{L^2(D_d)}.
\end{equation}

Now we bound $I_3$. Again, using the definition of $P_A$ and $r_{A,c}$, we get that

\[
I_3 = -\sum_{e \in E_h} \eta_e \int_e \langle P_A (\omega^2 r_{A,c}([u_h])) - \omega^2 r_{A,c}([u_h]) \rangle^T A[u_h] ds.
\]

After using (2.5), (2.3), Lemma 2.4 and (2.9), we have

\[ I_3 \leq C \sum_{e \in E_h} \|r_{A,c}([u_h])\|_{L^2(S_e)} (d^{-1}\|r_{A,c}([u_h])\|_{L^2(S_e)} + d^{-2} h\|r_{A,c}([u_h])\|_{L^2(S_e)}).
\]

By Lemma 2.5 and (2.5),

\[ h\|r_{A,c}([u_h])\|_{L^2(S_e)} \leq C \|u_h\|_{L^2(S_e)}.
\]

Therefore, after applying the arithmetic-geometric mean inequality, we get

\[ I_3 \leq C d^{-2}\|u_h\|_{L^2(D_d)}^2 + \epsilon \sum_{e \in E_h} \int_{S_e} \omega^2 r_{A,c}([u_h])^T A r_{A,c}([u_h]) dx.
\]

Now we handle $I_4$. By applying the product rule and the Cauchy-Schwarz inequality, using the boundedness of $c$ and $b$, the positive definiteness of $A$ and (2.3), we have that

\[
I_4 \leq C d^{-1}\|u_h\|_{L^2(D_d)}^2 + \epsilon \sum_{T \in T_h} \int_T \nabla (\omega u_h)^T A \nabla (\omega u_h) dx + \epsilon \sum_{e \in E_h} \frac{1}{h_e} \int_e (\omega[u_h])^T A(\omega[u_h]) ds.
\]

If we apply Lemma 2.7 followed by (2.3), we see that

\[
I_4 \leq C d^{-2}\|u_h\|_{L^2(D_d)}^2 + \epsilon \sum_{T \in T_h} \int_T \nabla (\omega u_h)^T A \nabla (\omega u_h) dx + C_1 \epsilon \sum_{e \in E_h} \int_{S_e} \omega^2 r_{A,c}([u_h])^T A r_{A,c}([u_h]) dx,
\]

where $C_1$ does not depend on $\epsilon$. Finally, by taking $\epsilon$ small enough to “kick back” we arrive at

\begin{equation}
I \leq CB(u_h, \omega^2 u_h) + C d^{-2}\|u_h\|_{L^2(D_d)}.
\end{equation}

Therefore, (3.3) holds for the Modified BRMPS form.

In order to work with the LDG form, we define $R(v) = r_A([v]) + l_A(\beta [v])$. Let us assume, for a moment, the following inequality:

\begin{equation}
\sum_{e \in E_h} \int_{S_e} \omega^2 r_{A,c}([u_h])^T A r_{A,c}([u_h]) dx + \sum_{e \in E_h} \int_{S_e} \omega^2 l_{A,c}(\beta [u_h])^T A l_{A,c}(\beta [u_h]) dx 
\leq C \sum_{e \in E_h} \frac{1}{h_e} \int_e \omega^2 [u_h]^2 ds + C d^{-2}\|u_h\|_{L^2(D_d)}.
\end{equation}
Using this inequality together with the fact that

\[ R(u_h) = \sum_{e} r_{A,e}([u_h]) + \sum_{e \in \mathcal{E}_h} l_{A,e}(\beta^T[u_h]) \]

and that \( r_{A,e} \) and \( l_{A,e} \) are both supported in \( S_e \), we have

\[
\int_{\Omega} \omega^2 R(u_h)^T A R(u_h) dx \leq C \sum_{e \in \mathcal{E}_h} \frac{1}{h_e} \int_{e} \omega^2 [u_h]^2 ds + Cd^{-2} \|u_h\|_{L^2(D_d)}.
\]

Using (3.16), we get

\[
\|\omega u_h\|^2_{H^1(\Omega)} \leq CJ + Cd^{-2} \|u_h\|^2_{L^2(D_d)},
\]

where

\[
J \equiv \sum_{T \in \mathcal{T}_h} \int_{T} \nabla(\omega u_h)^T A \nabla(\omega u_h) dx + \sum_{e \in \mathcal{E}_h} \frac{1}{h_e} \int_{e} [\omega u_h]^2 ds.
\]

Recall that for the LDG form \( \eta > 0 \). Using this fact, the arithmetic-geometric mean inequality and \([3.10]\) we have (see (4.16) in [2] for a similar inequality)

\[
J \leq C \left( \sum_{T \in \mathcal{T}_h} \int_{T} \nabla(\omega u_h)^T A \nabla(\omega u_h) dx + 2 \sum_{T \in \mathcal{T}_h} \int_{T} \omega R(u_h)^T A \nabla(\omega u_h) dx \right)
\]

\[
+ \int_{\Omega} \omega^2 R(u_h)^T A R(u_h) dx + \sum_{e \in \mathcal{E}_h} \frac{\eta_c}{h_e} \int_{e} [\omega u_h]^2 ds + Cd^{-2} \|u_h\|_{L^2(D_d)}.
\]

Adding and subtracting the terms of \( B(u_h, \omega^2 u_h) \) from the right-hand side of (3.17) we see that

\[
J \leq CB(u_h, \omega^2 u_h) + C(J_1 + J_2 + J_3 + J_4) + Cd^{-2} \|u_h\|_{L^2(D_d)},
\]

where

\[
J_1 = \left| \sum_{T \in \mathcal{T}_h} \int_{T} \nabla(\omega u_h)^T A \nabla(\omega u_h) dx - \nabla(\omega^2 u_h)^T A \nabla(\omega u_h) dx \right|
\]

\[
J_2 = \left| 2 \sum_{T \in \mathcal{T}_h} \int_{T} \omega R(u_h)^T A \nabla(\omega u_h) dx \right|
\]

\[
+ \sum_{e \in \mathcal{E}_h} \int_{e} \left( \langle A \nabla_h(\omega^2 u_h) \rangle [u_h] + \langle A \nabla_h u_h \rangle [\omega^2 u_h] ds \right)
\]

\[
+ \sum_{e \in \mathcal{E}_h} \int_{e} \left( \langle A \nabla_h(\omega^2 u_h) \rangle [\beta^T[u_h]] + \langle A \nabla_h u_h \rangle [\beta^T[\omega^2 u_h]] ds \right)
\]

\[
J_3 = \left| \int_{\Omega} \omega^2 R(u_h)^T A R(u_h) dx - \int_{\Omega} R(\omega^2 u_h)^T A R(u_h) dx \right|
\]

and

\[
J_4 = \left| \sum_{T \in \mathcal{T}_h} \int_{T} (c(\omega u_h)^2 + u_h b \cdot \nabla(\omega^2 u_h) dx + \sum_{e \in \mathcal{E}_h} \int_{e} \langle u_h \rangle b \cdot [\omega^2 u_h] ds \right|.
\]

We see that \( J_1 \) is \( |I_1| \) with \( u_h \) now being the LDG solution. Therefore,

\[
J_1 \leq Cd^{-2} \|u_h\|^2_{L^2(D_d)}.
\]
After following similar manipulations as was done to simplify $I_2$, we get
\[
J_2 = 2 \sum_{e \in E_h} \int_{e} (P_A(\omega \nabla_h(\omega u_h)) - \omega \nabla_h(\omega u_h))^T A[u_h]ds \\
+ 2 \sum_{e \in E_h} \int_{e} [A(P_A(\omega \nabla_h(\omega u_h)) - \omega \nabla_h(\omega u_h))]\beta^T [u_h]ds.
\]

Using, (2.3), (2.5), Lemma 2.4, and (2.10), we have
\[
J_2 \leq \epsilon \sum_{T \in I_h} \int_{T} \nabla(\omega u_h)^T A \nabla (\omega u_h)dx + C d^{-2} ||u_h||_{L_2(D_d)}.
\]

Using the definitions of our lifting operators and the projection operator, as was done for $I_3$, we see that
\[
J_3 = \left| \sum_{e \in E_h} \int_{e} (P_A(\omega^2 R(u_h)) - \omega^2 R(u_h))^T A[u_h]ds \\
+ \sum_{e \in E_h} \int_{e} [A(P_A(\omega^2 R(u_h)) - \omega^2 R(u_h))]\beta^T [u_h]ds. \right|
\]

Using the Cauchy-Schwarz inequality, (2.3), and (2.10), we have
\[
J_3 \leq C \sum_{e \in E_h} h^{-1/2} ||u_h||_{L_2(S_e)} (h^{-1/2} ||P_A(\omega^2 R(u_h)) \\
- \omega^2 R(u_h)||_{L_2(S_e)} + h^{1/2} ||P_A(\omega^2 R(u_h)) - \omega^2 R(u_h)||_{H^1(S_e)}).
\]

Using the fact that $P_A$ is linear, the definition of $R$, and the fact that the supports of $r_{A,e}$, $l_{A,e}$ lie in $S_e$, we have
\[
J_3 \leq C \sum_{e \in E_h} h^{-1/2} ||u_h||_{L_2(S_e)} (h^{-1/2} ||P_A(\omega^2 r_{A,e}([u_h])) - \omega^2 r_{A,e}([u_h])||_{L_2(S_e)} \\
+ h^{1/2} ||P_A(\omega^2 r_{A,e}([u_h])) - \omega^2 r_{A,e}([u_h])||_{H^1(S_e)}) \\
+ C \sum_{e \in E_h} h^{-1/2} ||u_h||_{L_2(S_e)} (h^{-1/2} ||P_A(\omega^2 l_{A,e}(\beta^T [u_h])) - \omega^2 l_{A,e}(\beta^T [u_h])||_{L_2(S_e)} \\
+ h^{1/2} ||P_A(\omega^2 l_{A,e}(\beta^T [u_h])) - \omega^2 l_{A,e}(\beta^T [u_h])||_{H^1(S_e)}).
\]

Here $S_e'$ denotes $S_e$ union with the triangles that share an edge with $S_e$. Finally, mimicking the argument for bounding $I_3$, we see that
\[
J_3 \leq C d^{-2} ||u_h||_{L_2(D_d)} + \epsilon \sum_{e \in E_h} \int_{S_e} (\omega^2 r_{A,e}([u_h])^T A r_{A,e}([u_h]))dx \\
+ \epsilon \sum_{e \in E_h} \int_{S_e} (\omega^2 l_{A,e}(\beta^T [u_h])^T A l_{A,e}(\beta^T [u_h]))dx.
\]

Furthermore, by (3.10),
\[
(3.18) \quad J_3 \leq C d^{-2} ||u_h||_{L_2(D_d)} + C_1 \epsilon \sum_{e \in E_h} \frac{1}{h_e} \int_{e} [\omega u_h]^2 ds,
\]
where \( C_1 \) is independent of \( \epsilon \). Again, since \( J_4 \) is \(|I_4|\) with \( u_h \) now being the LDG solution, we have

\[
J_4 \equiv I_4 \leq C d^{-2}||u_h||^2_{L^2(D_d)} + \epsilon \sum_{T \in T_h} \int_T \nabla(u_h)^T A \nabla(u_h)dx + \epsilon \sum_{e \in \mathcal{E}_h} \frac{1}{h_e} \int [\omega u_h]^2 ds.
\]

Finally, taking \( \epsilon \) sufficiently small to “kick back”, we conclude that

\[
J \leq C B(u_h, \omega^2 u_h) + Cd^{-2}||u_h||^2_{L^2(D_d)}.
\]

This, of course, implies (3.3) for the LDG form, which in turn implies our theorem for the LDG form. We are left to show (3.15).

In bounding \( I_3 \), we showed that

\[
(3.19) \quad |\sum_{e \in \mathcal{E}_h} \int_{S_e} (\omega^2 r_{A,e}([u_h])^T A r_{A,e}([u_h]) - r_{A,e}(\omega^2[u_h])^T A r_{A,e}([u_h]))dx| 
\]

\[
\leq C d^{-2}||u_h||^2_{L^2(D_d)} + \epsilon \sum_{e \in \mathcal{E}_h} \int_{S_e} \omega^2(r_{A,e}([u_h]))^T A(r_{A,e}([u_h]))dx,
\]

where \( \epsilon > 0 \) is arbitrary. Following similar steps one can show

\[
(3.20) \quad |\sum_{e \in \mathcal{E}_h} \int_{S_e} (\omega^2 l_{A,e}(\beta^T[u_h])^T A l_{A,e}(\beta^T[u_h]) - l_{A,e}(\omega^2 \beta^T[u_h])^T A l_{A,e}(\beta^T[u_h]))dx| 
\]

\[
\leq C d^{-2}||u_h||^2_{L^2(D_d)} + \epsilon \sum_{e \in \mathcal{E}_h} \int_{S_e} \omega^2(l_{A,e}(\beta^T[u_h]))^T A(l_{A,e}(\beta^T[u_h]))dx.
\]

By an inverse estimate, (2.5), and the arithmetic-geometric mean inequality, we have

\[
(3.21) \quad |\sum_{e \in \mathcal{E}_h} \int_{S_e} r_{A,e}(\omega^2[u_h])^T A r_{A,e}([u_h])dx| 
\]

\[
+ |\sum_{e \in \mathcal{E}_h} \int_{S_e} l_{A,e}(\omega^2 \beta^T[u_h])^T A l_{A,e}(\beta^T[u_h])dx|
\]

\[
= |\sum_{e \in \mathcal{E}_h} \int_{S_e} \omega[u_h]^T A (r_{A,e}([u_h])) ds| + |\sum_{e \in \mathcal{E}_h} \int_{S_e} \omega \beta^T[u_h][\omega A l_{A,e}(\beta^T[u_h])]ds|
\]

\[
\leq C \sum_{e \in \mathcal{E}_h} \frac{1}{h_e} \int [\omega u_h]^2 ds + \epsilon \sum_{e \in \mathcal{E}_h} \int_{S_e} \omega^2 r_{A,e}([u_h])^T A r_{A,e}([u_h])dx
\]

\[
+ \epsilon \sum_{e \in \mathcal{E}_h} \int_{S_e} \omega^2 l_{A,e}(\beta^T[u_h])^T A l_{A,e}(\beta^T[u_h])dx.
\]

Using (3.19), (3.20), (3.21), the triangle inequality, and taking \( \epsilon \) sufficiently small to “kick back”, we arrive at (3.15).

Following similar techniques as those shown above, we can show (3.3) for the Modified BMMPR form. We omit the proof. \( \square \)
Using approximation properties and Theorem 3.1, we have the following corollary.

**Corollary 3.2.** Let \( x, D_0, D_d, u, \) and \( u_h \) be as in Theorem 3.1. Then
\[
\| u - u_h \|_{H^1_h(D_h)} \leq Ch \| u \|_{H^r(D_d)} + Cd^{-1} \| u - u_h \|_{L_2(D_d)}.
\]

### 4. Pointwise estimates

Now we are ready to state our pointwise error estimates.

**Theorem 4.1.** Suppose \( u \in W^{1,\infty}(\Omega) \) satisfies (2.1) and \( u_h \in V_h \) satisfies (2.2) for any of the bilinear forms. Let \( x \in \bar{\Omega} \) and \( s \) satisfy \( 0 \leq s \leq r - 2, r \geq 2 \). Then, there exists a constant \( C \) independent of \( x, u, u_h \) and \( h \) such that
\[
| (u - u_h)(x) | \leq C h \log(1/h)^\bar{s} \inf_{\chi \in V_h} \| u - \chi \|_{W^{1,\infty}_h(\Omega), x, s},
\]
where \( \bar{s} = 0 \) if \( 0 \leq s < r - 2 \), and \( \bar{s} = 1 \) if \( s = r - 2 \).

**Proof.** Now that we have established Lemma 2.6 and Corollary 3.2, we can follow the techniques of the proof for Theorem 5.1 in [6]. The main difference is that their result does not handle hanging nodes. However, their proof can easily be modified to allow hanging nodes by using the fact that each element has at most \( K \) neighbors. Also, the norm appearing on the right-hand side of our result has an extra term, but that term can be handled easily throughout their proof. \( \square \)

Similarly, by following the proof of Theorem 5.2 in [6], we obtain gradient pointwise estimates.

**Theorem 4.2.** Suppose \( u \in W^{1,\infty}(\Omega) \) satisfies (2.1) and \( u_h \in V_h \) satisfies (2.2) for any of the bilinear forms. Let \( x \in \bar{\Omega} \) and \( s \) satisfy \( 0 \leq s \leq r - 1, r \geq 2 \). Then, there exists a constant \( C \) independent of \( x, u, u_h \) and \( h \) such that
\[
| \nabla_h (u - u_h)(x) | \leq C h \log(1/h)^\bar{s} \inf_{\chi \in V_h} \| u - \chi \|_{W^{1,\infty}_h(\Omega), x, s},
\]
where \( \bar{s} = 0 \) if \( 0 \leq s < r - 1 \), and \( \bar{s} = 1 \) if \( s = r - 1 \).

The results here carry over to higher dimensions, if we allow meshes that fit the boundary exactly. Of course, this is not practical in higher dimensions, but it can in principle be done. Let \( \Omega' \) satisfy \( \Omega \subset \Omega' \) and \( \text{dist}(\partial \Omega, \partial \Omega') \leq Ch^2 \). If we mesh the larger domain \( \Omega' \) with simplices such that the simplicial domain contains \( \Omega \) and then restrict the mesh to \( \Omega \), we will find our desired mesh.

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**References**


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