A numerical study on the finite element solution of singularly perturbed systems of reaction-diffusion problems*

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Abstract

We consider the approximation of singularly perturbed systems of reaction-diffusion problems, with the finite element method. The solution to such problems contains boundary layers which overlap and interact, and the numerical approximation must take this into account in order for the resulting scheme to converge uniformly with respect to the singular perturbation parameters. In this article we perform a numerical study of several finite element methods applied to a model problem, having as our goal their assessment and the identification of a high order scheme which approximates the solution at an exponential rate of convergence, independently of the singular perturbation parameters.

1 Introduction

The numerical solution of singularly perturbed problems has been studied extensively over the last decade (see, e.g., the books [12], [13], [15] and the references therein). The main difficulty in these problems is the presence of *boundary layers* in the solution, whose accurate approximation, independently of the singular perturbation parameter(s), is of utmost importance in order for the overall quality of the approximate solution to be good. In the context of the Finite Element Method (FEM), the robust approximation approximation of boundary layers requires either the use of the h version on non-uniform meshes (such as the Shishkin [18] or Bakhvalov [1] mesh), or the use of the high order p and hp versions on specially designed (variable) meshes [19]. In both cases, the a-priori knowledge of the position of the layers is taken into account, and mesh-degree combinations can be chosen for which uniform error estimates can be established [5], [19].

In this article we consider a *system* of two coupled singularly perturbed linear reaction-diffusion equations, which have two overlapping boundary layers. This problem was studied by Matthews et al. [9, 10], Madden and Stynes [8] and by Linß and Madden [6, 7] in the context of finite differences, and by Linß and Madden [5] in the context of the h version of the FEM with piecewise linear basis functions. Here we consider the finite element approximation of the same problem, paying particular attention to the high order versions of the FEM. Our goal is to numerically investigate the performance of all versions of the FEM on various meshes and to identify a method which approximates the solution independently of the singular perturbation parameters at a sufficiently fast rate. In fact, we propose a p/hp FEM on a 5 element variable mesh which, as our numerical computations will demonstrate, approximates the solution at an *exponential* rate of convergence, independently of the singular perturbation parameters.

The rest of the paper is organized as follows: In Section 2 we present the model problem and discuss the properties of its solution. In Section 3 we give the finite element formulation and the design of the various

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schemes we will be considering. Section 4 contains the results of extensive numerical computations in order to assess the performance of each method, and finally, in Section 5 we summarize our conclusions.

In what follows, the space of squared integrable functions on an interval $\Omega \subset \mathbb{R}$ will be denoted by $L^2(\Omega)$, with associated inner product

$$(u,v)_\Omega := \int_\Omega uv.$$

We will also utilize the usual Sobolev space notation $H^k(\Omega)$ to denote the space of functions on Ω with $0,1,2,...,k$ generalized derivatives in $L^2(\Omega)$, equipped with norm and seminorm $\|\cdot\|_{\Omega,1}$ and $|\cdot|_{\Omega,1}$, respectively. For vector functions $\overrightarrow{u} = [u_1(x), u_2(x)]^T$, we will write

$$\|\overrightarrow{u}\|^2_{\Omega,k} = \|u_1\|^2_{\Omega,k} + \|u_2\|^2_{\Omega,k}.$$

We will also use the space

$$H^1_0(\Omega) = \left\{ u \in H^1(\Omega) : u|_{\partial\Omega} = 0 \right\},$$

where $\partial\Omega$ denotes the boundary of Ω. Finally, the letter C will be used to denote a generic positive constant, independent of any discretization or singular perturbation parameters and possibly having different values in each occurrence.

2 The model problem

As in [5]–[10], we consider the following model problem:

$$L\overrightarrow{u} := \begin{bmatrix} -\varepsilon^2 \frac{d^2}{dx^2} & 0 \\ 0 & -\mu^2 \frac{d^2}{dx^2} \end{bmatrix} \overrightarrow{u} + A\overrightarrow{u} = \overrightarrow{f} \text{ in } \Omega = (0,1), \tag{1}$$

along with the boundary conditions on $\partial\Omega$

$$\overrightarrow{u}(0) = \overrightarrow{\gamma}_0, \ \overrightarrow{u}(1) = \overrightarrow{\gamma}_1. \tag{2}$$

In (1)–(2) the parameters ε and μ lie in $(0,1]$,

$$A = \begin{bmatrix} a_{11}(x) & a_{12}(x) \\ a_{21}(x) & a_{22}(x) \end{bmatrix}, \ \overrightarrow{f} = \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} \tag{3}$$

are given, and we will take, without loss of generality, $\overrightarrow{\gamma}_0 = \overrightarrow{\gamma}_1 = \overrightarrow{0}$ in (2). Moreover, we will assume that the matrix A is invertible and that there exists some constant α such that

$$\min_{[0,1]} \{a_{11}(x) + a_{12}(x), a_{21}(x) + a_{22}(x)\} > \alpha^2 > 0. \tag{4}$$

Problems of this type arise in the study of turbulence models [14], [20], population dynamics [4], as well as in the modeling of mass transfer processes in multicomponent systems [17]. Moreover, when $\mu = 1$, the system (1)–(2) corresponds to the scalar fourth order singularly perturbed problem studied in [16], hence our treatment contains this as a special case.

We will concentrate on the most interesting case (see, e.g., [8]) when

$$0 < \varepsilon \leq \mu \leq 1,$$

and our goal will be to obtain a finite element approximation for the solution $\overrightarrow{u} := [u_1(x), u_2(x)]^T$ to (1)–(2), that is valid *uniformly* in ε and μ, i.e. the method does not deteriorate as $\varepsilon, \mu \to 0$. It is known that in this case the solution $\overrightarrow{u}$ will contain boundary layers of width $O\left(\left|\mu^{1/2}\ln\mu\right|\right)$, but as it was shown in [8], the first component of $\overrightarrow{u}$ will contain an additional sublayer of width $O\left(\left|\varepsilon^{1/2}\ln\varepsilon\right|\right)$. This is demonstrated in figure 1 below, in which the two components of the solution $\overrightarrow{u}$ are shown, for the case

$$A = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}, \overrightarrow{f}(x) = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \overrightarrow{u}(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \varepsilon = 10^{-7}, \mu = 10^{-4}. \tag{5}$$

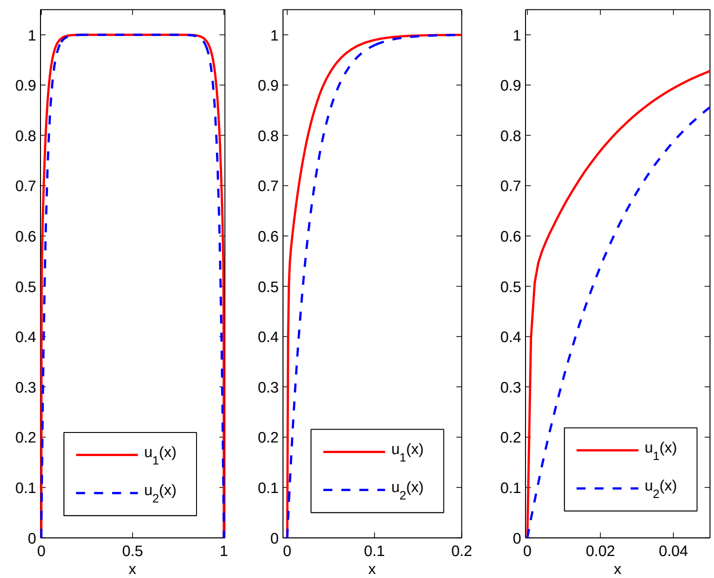

Figure 1: The exact solution of (1)–(2) for the example given by (5).

In [8], it was shown that the solution to (1)–(2) can be decomposed into a smooth part and a boundary layer part, and bounds on each were obtained which allowed for the design of a uniformly (in ε and μ) convergent finite difference scheme on a Shishkin mesh, to be constructed. These bounds were subsequently utilized in [5] for the design of a piecewise linear finite element scheme (on Shishkin and Bakhvalov meshes), which again was shown to be uniformly convergent. In particular, the results of [8] state that if $\overrightarrow{u}$ solves (1)–(2), and $\overrightarrow{U}$ is the approximation obtained using centered second order finite differences on a Shishkin mesh with nodes $\{x_i\}_{i=0}^N$, then

$$\left\| \overrightarrow{u} - \overrightarrow{U} \right\|_N \leq CN^{-1} \ln N, \tag{6}$$

where $\|\overrightarrow{u}\|_N = \max\limits_{k=1,2} \left\{ \max\limits_{i=0,\ldots,N} |u_k(x_i)| \right\}$. The error estimate (6) was improved in [7] where it was shown that the same central difference scheme gives almost second order accuracy (as opposed to almost first order accuracy shown in [8]); see also [6]. A similar error estimate to (6) was also obtained in [5], in terms of the energy norm (see (12) ahead), with $\overrightarrow{U}$ being the piecewise linear finite element approximation on the Shishkin mesh. More details on the finite element approximation of this problem, and the error estimates obtained in [5], will be given in the next section.

An example of the Shishkin mesh used in the articles mentioned above is shown in figure 2, in which

$$\tau_\mu = \min\left\{ \frac{1}{4}, \frac{\sqrt{\mu}}{\alpha} \ln N \right\} \ , \ \tau_\varepsilon = \min\left\{ \frac{1}{8}, \frac{\tau_\mu}{2}, \frac{\sqrt{\varepsilon}}{\alpha} \ln N \right\}. \tag{7}$$

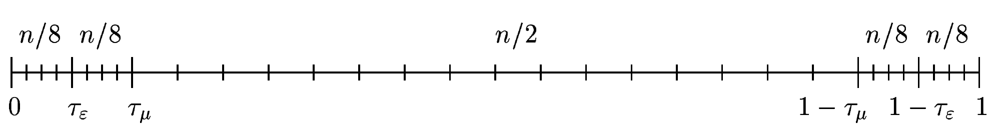

Figure 2: Example of a Shishkin mesh with $n = 32$ subintervals.

3 The finite element methods

As usual, we cast the problem (1)–(2) into an equivalent weak formulation, which reads: Find $\overrightarrow{u} \in \left[H_0^1(\Omega)\right]^2$ such that

$$B(\overrightarrow{u}, \overrightarrow{v}) = F(\overrightarrow{v}) \quad \forall \overrightarrow{v} \in \left[H_0^1(\Omega)\right]^2, \tag{8}$$

where

$$\begin{aligned} B(\overrightarrow{u}, \overrightarrow{v}) &= \varepsilon^2 (u_1', v_1')_\Omega + \mu^2 (u_2', v_2')_\Omega + (a_{11}u_1 + a_{12}u_2, v_1)_\Omega + (a_{21}u_1 + a_{22}u_2, v_2)_\Omega, & (9)\\ F(\overrightarrow{v}) &= (f_1, v_1)_\Omega + (f_2, v_2)_\Omega. & (10) \end{aligned}$$

From (4), we get that for any $x \in \Omega$,

$$\overrightarrow{\xi}^T A \overrightarrow{\xi} \geq \alpha^2 \overrightarrow{\xi}^T \overrightarrow{\xi} \quad \forall \overrightarrow{\xi} \in \mathbb{R}^2, \tag{11}$$

and it follows that the bilinear form $B(\cdot,\cdot)$ is coercive with respect to the *energy norm*

$$\|\overrightarrow{u}\|_{E,\Omega}^2 := \varepsilon^2 |u_1|_{1,\Omega}^2 + \mu^2 |u_2|_{1,\Omega}^2 + \alpha^2 \left(\|u_1\|_{0,\Omega}^2 + \|u_2\|_{0,\Omega}^2\right), \tag{12}$$

i.e.,

$$B(\overrightarrow{u}, \overrightarrow{u}) \geq \|\overrightarrow{u}\|_{E,\Omega}^2 \quad \forall \overrightarrow{u} \in \left[H_0^1(\Omega)\right]^2. \tag{13}$$

This, along with the continuity of $B(\cdot,\cdot)$ and $F(\cdot)$, imply the unique solvability of (8).

For the discretization, we choose a finite dimensional subspace V_N of $H_0^1(\Omega)$ and solve the problem: Find $\overrightarrow{u}_N \in [V_N]^2$ such that

$$B(\overrightarrow{u}_N, \overrightarrow{v}) = F(\overrightarrow{v}) \quad \forall \overrightarrow{v} \in [V_N]^2. \tag{14}$$

The unique solvability of the discrete problem (14) follows from (11) and (13). The subspace V_N is chosen as follows: Let $\Delta = \{0 = x_0 < x_1 < ... < x_M = 1\}$ be an arbitrary partition of $\Omega = (0,1)$ and set

$$\begin{aligned} I_j &= (x_{j-1}, x_j), \; h_j = x_j - x_{j-1}, \; j = 1, ..., M, \\ h_{\max} &= \max_{j=1,\dots,M} h_j. \end{aligned}$$

Also, define the master (or standard) element $I_{ST} = (-1,1)$, and note that it can be mapped onto the j^{th} element I_j by the linear mapping

$$x = Q_j(t) = \frac{1}{2}(1-t)\, x_{j-1} + \frac{1}{2}(1+t)\, x_j.$$

The inverse mapping, which maps the j^{th} element onto the standard element, is given by

$$t = Q_j^{-1}(x) = \frac{2t - x_{j-1} - x_j}{h_j}.$$

With $\Pi_p(I_{ST})$ the space of polynomials of degree $\leq p$ on I_{ST}, we define our finite dimensional subspace as

$$V_N \equiv V_N(\Delta, \overrightarrow{p}) = \left\{u \in H_0^1(\Omega) : u(Q_j(t)) \in \Pi_{p_j}(I_{ST}), j = 1, ..., M\right\}, \tag{15}$$

where $\overrightarrow{p} = (p_1, ..., p_M)$ is the vector of polynomial degrees assigned to the elements. This construction allows us to study all the versions of the FEM, namely: (i) the h version, in which $\overrightarrow{p}$ is fixed and $h_{\max} \to 0$, (ii) the p version, in which the mesh (i.e. h_j) is fixed and $p_j \to \infty \; \forall j$, and (iii) the hp version, which is a combination of the previous two. We will focus our attention to the design of a high order p/hp FEM on a suitable (variable) mesh, which will approximate the solution to (1)–(2) uniformly in ε and μ, at an *exponential* rate.

The idea for a high order method for singularly perturbed problems comes from the study of the scalar problem

$$\begin{aligned} -\varepsilon^2 u''(x) + b(x)u(x) &= f(x) \;\text{ in }\; \Omega = (0,1), & (16)\\ u(0) &= u(1) = 0. & (17) \end{aligned}$$

Schwab and Suri [19] showed that, in the case $b(x) =$ constant, the use of the three element mesh

$$\Delta = \{0, p\varepsilon, 1-p\varepsilon, 1\}, \tag{18}$$

in conjunction with the p version of the FEM yields exponential convergence rates, independently of ε, when the error is measured in the energy norm (see also [21]). In (18), the degree p of the approximating polynomials is increased until $\varepsilon p \approx 1$; once $p \approx \varepsilon^{-1}$, we enter the asymptotic range of p and using the p version on a single element yields exponential convergence (see [19] for more details). The non-constant coefficient case of problem (16)–(17) was studied by Melenk [11], where the exponential convergence rate was established for any b and f which are analytic.

In terms of the h version of the FEM for problem (16)–(17), the use of piecewise polynomials of degree p on a Shishkin mesh with $O(N)$ elements, is known to yield the quasi-optimal algebraic convergence rate $O\left(\left(N^{-1}\ln N\right)^p\right)$ [23]. The optimal algebraic rate $O\left(N^{-p}\right)$ for the h version can be attained if a Bakhvalov mesh [1], or an exponentially graded mesh is used (cf. [2], [3], [22]). The exponentially graded mesh for the scalar problem (16)–(17) is defined as $\Delta = \left\{x_j^\varepsilon\right\}_{j=0}^N$, where

$$x_j^\varepsilon = \frac{1}{2}\varepsilon\,(2p+1)\ln\left(1-\frac{s_j}{N}\right) \text{ with } s_j = 1-\exp\left(-\frac{2}{\varepsilon\,(2p+1)}\right), \tag{19}$$

and is shown in figure 3 (see [22] for more details.)

Figure 3: Example of the exponentially graded mesh with $N = 12$ nodes.

Guided by the above results for the scalar problem, and the behavior of the overlapping layers for the system (1)–(2), we design the following finite element schemes: For the p/hp version, we use the five element variable mesh

$$\Delta = \{0, p\varepsilon, p\mu, 1-p\mu, 1-p\varepsilon, 1\}, \tag{20}$$

with p increasing, under the assumptions that $0 < p\varepsilon < p\mu$ and $1-p\mu < 1-p\varepsilon < 1$. If $\max\{p\varepsilon, p\mu\} \approx 1$ then we simply use a single element and increase p. Moreover, if $\varepsilon = \mu$ or either ε or $\mu = 1$, then we use the three element mesh (18). As our numerical results in the next section will indicate, this scheme will yield exponential convergence, independently of ε and μ, and the following error estimate will be observed:

$$\|\vec{u} - \vec{u}_N\|_{E,\Omega} \leq C\max\left\{\varepsilon^{1/2}, \mu^{1/2}\right\}e^{-\kappa p}, \ \kappa \in \mathbb{R}^+. \tag{21}$$

(The proof of (21) appears in [24]). For the h version, we will construct an exponentially graded mesh, suitable for the system (1)–(2), by taking the union of the meshes obtained using (19) once with ε and once with ε replaced by μ, i.e. $\Delta = \left\{x_j^\varepsilon\right\}_{j=0}^N \cup \left\{x_j^\mu\right\}_{j=0}^N$. As our numerical computations in the next section will indicate, this method will yield the optimal convergence rate $O\left(N^{-p}\right)$. We will also consider the h version on a Shishkin mesh, with polynomials of degree $p = 1, 2$ and 3. Since the definition of the mesh from [5], [8], seen in figure 2, corresponds to $p = 1$, we will take

$$\tau_\mu = \min\left\{\frac{1}{4}, \frac{\sqrt{\mu}}{\alpha}(p+1)\ln N\right\}, \ \tau_\varepsilon = \min\left\{\frac{1}{8}, \frac{\tau_\mu}{2}, \frac{\sqrt{\varepsilon}}{\alpha}(p+1)\ln N\right\}$$

instead of (7), for our computations.

Remark 1 *We choose not to consider the Bakhvalov mesh in this study, mainly because its construction requires the solution of a nonlinear problem for the determination of the nodal points in the mesh (see [1] for* *details). Since the exponentially graded mesh mentioned above yields the same $O(N^{-p})$ convergence rate and its construction can be made a-priori without solving any nonlinear problems, we feel it is a more suitable choice for our study.*

We close this section by mentioning the error estimates obtained in [5] for the model problem (1)–(2) using the finite element method with piecewise linear basis functions. For the Shishkin mesh, it was shown that

$$\|\vec{u} - \vec{u}_N\|_{E,\Omega} \leq CN^{-1} \ln N,$$

and for the Bakhvalov mesh, the following was established

$$\|\vec{u} - \vec{u}_N\|_{E,\Omega} \leq CN^{-1},$$

with the positive constants C independent of N, ε and μ. Our computations in the next section will suggest that the above error estimate for the Shishkin mesh can be generalized for polynomials of degree $p \geq 1$.

4 Numerical results

In this section we present the results of numerical computations for the two model problems considered in [5], [8]. Our goal will be to compare the different types of finite element schemes, as well as verify the claims made in Section 3 regarding the high order FEMs and the h version on the exponentially graded mesh. Also, we will present results for the Shishkin mesh with $p = 2$ and 3 (in addition to $p = 1$), which, as mentioned above, suggest that the results in [5] can be generalized.

4.1 The constant coefficient case

First we consider the constant coefficient case, in which

$$A = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix}, \vec{f}(x) = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \vec{u}(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

An exact solution is available, hence the computations we report are reliable. We will be comparing the following methods:

- The h version on a uniform mesh, with $p = 1, 2$ and 3.
- The p version on a single element.
- The hp version on the 5 element (variable) mesh given by (20).
- The h version on a Shishkin mesh, with $p = 1, 2$ and 3.
- The h version on the exponentially graded mesh given by (19), with $p = 1, 2$ and 3.

We expect that the first two methods will not be robust, while the last three will. We will be plotting the percentage relative error in the energy norm, given by

$$100 \times \frac{\|\vec{u}_{EXACT} - \vec{u}_{FEM}\|_{E,\Omega}}{\|\vec{u}_{EXACT}\|_{E,\Omega}}, \tag{22}$$

versus the number of degrees of freedom N, on a log-log scale.

Figure 4 shows the error when $\varepsilon = 0.4$ and $\mu = 1$. Since these values are "large", we see that the h version on a uniform mesh performs sufficiently well (with $O\left(N^{-p}\right)$ convergence rate), and the p version on a single element yields exponential convergence.

In figure 5, which corresponds to $\varepsilon = 0.01$ and $\mu = 0.1$, we see the performance of the aforementioned methods beginning to deteriorate, even though the p version still converges exponentially due to the fact that we continue to have $p \approx \varepsilon^{-1}$.

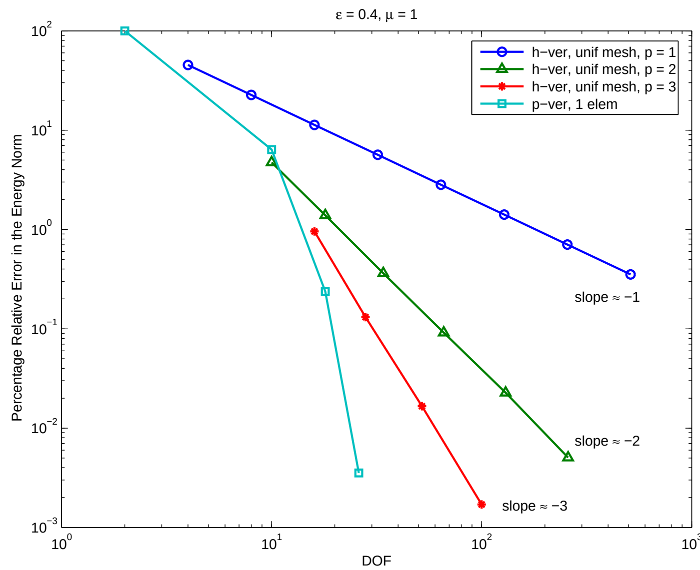

Figure 4: Energy norm convergence for $\varepsilon = 0.4$ and $\mu = 1$.

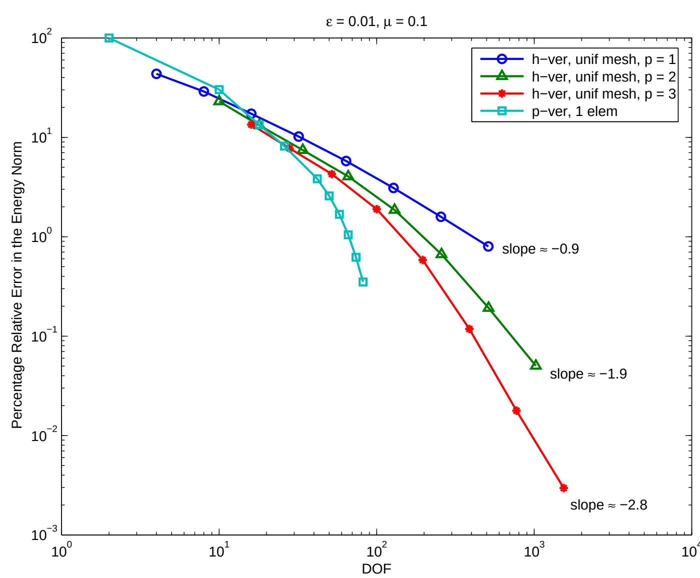

Figure 5: Energy norm convergence for $\varepsilon = 0.01$ and $\mu = 0.1$.

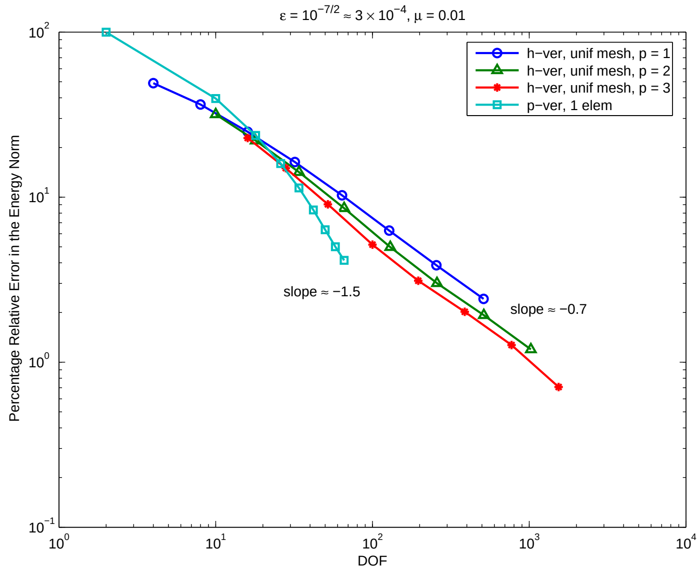

Figure 6: Energy norm convergence for $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ and $\mu = 0.01$.

The deterioration of these methods is seen in figure 6 which corresponds to $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ and $\mu = 0.01$. We observe that the h version on a uniform mesh converges at the rate $O\left(N^{-0.7}\right)$, independently of the polynomial degree used, while the p version no longer converges exponentially, but at the algebraic rate $O\left(N^{-1.5}\right)$ which is roughly twice that of the h version.

For these values of ε and μ, we show in figure 7 the behavior of the h version on the uniform, Shishkin and exponential meshes with $p = 1$, the p version on 1 element and the hp version on 5 elements. This figure clearly indicates the robustness of the h version on the Shishkin and exponential meshes, as well as the exponential convergence of the hp version on the 5 element mesh.

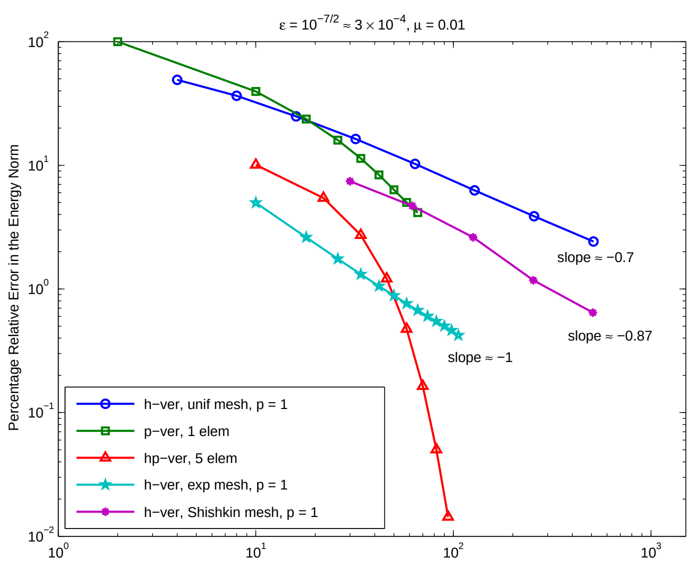

Figure 7: Energy norm convergence for $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ and $\mu = 0.01$.

Figure 8 shows the behavior of the robust h versions with different polynomial degrees. We see that the exponential mesh produces the optimal algebraic rate $O\left(N^{-p}\right)$, while the Shishkin mesh yields the (usual) quasi-optimal rate $O\left(\left(N^{-1}\ln N\right)^p\right)$, with the logarithmic term not removable. For completeness, we have included the hp version to see how it compares with the robust h versions, and we see that only the h version on the exponential mesh is comparable to it.

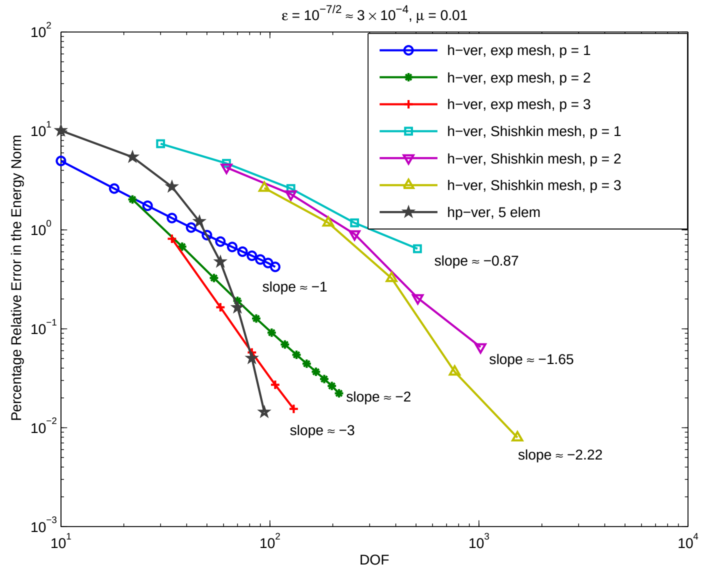

Figure 8: Energy norm convergence for $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ and $\mu = 0.01$.

The situation remains the same as ε and μ decrease even further, as is shown in figure 9, which corresponds to $\varepsilon = 10^{-5}$ and $\mu = 10^{-3}$ (smaller values for ε and μ produce almost identical results).

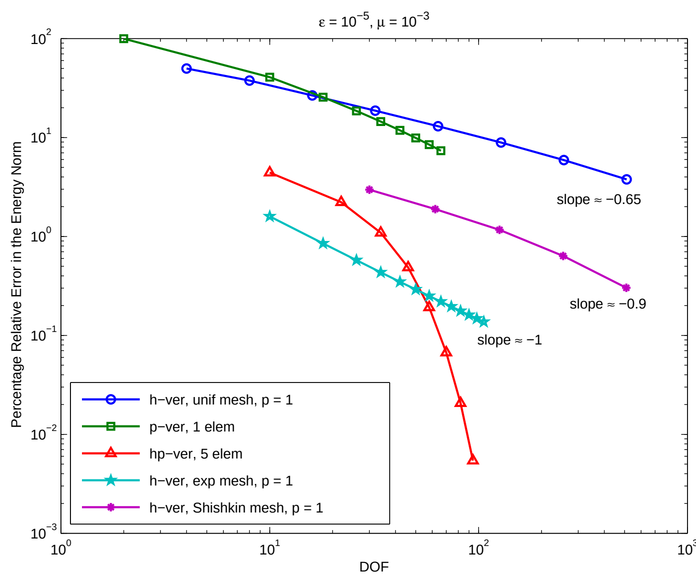

Figure 9: Energy norm convergence for $\varepsilon = 10^{-5}$ and $\mu = 10^{-3}$.

We also show, in figure 10, the hp version on the 5 element mesh, for different values of ε and μ, and we observe that the method not only does not deteriorate as $\varepsilon, \mu \to 0$, but it actually performs better, when the error is measured in the energy norm. This is reflected by the positive powers of ε and μ in the error estimate (21). Although not shown, this behavior is also present in the h version on the exponential mesh.

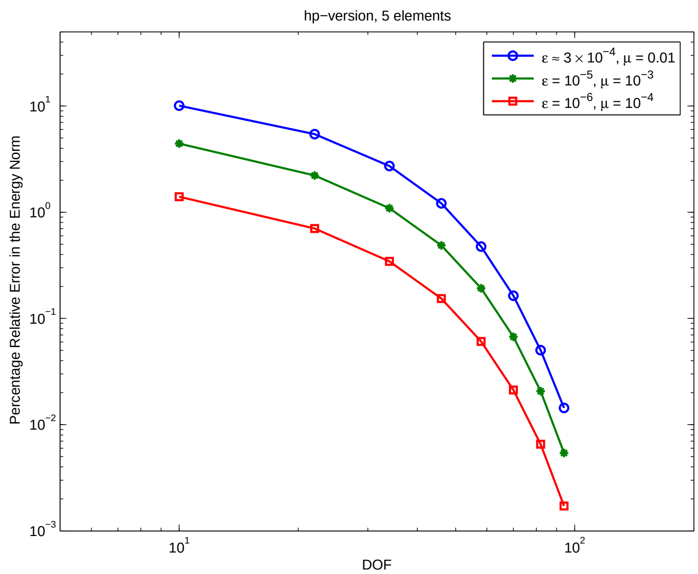

Figure 10: Energy norm convergence for the *hp* version.

Remark 2 *Strictly speaking, the hp scheme considered here is not a* true *hp FEM, since the position, and not the number of elements, is changing as p is increased. A more accurate characterization of this scheme would be a p version FEM on an appropriately designed (variable) mesh. It is possible, nonetheless, to obtain a true hp FEM by using the exponentially graded mesh (or even the Shishkin mesh) in conjunction with increasing p. This is shown in figure 11 below, in which we see how the true hp version (using the exponential mesh) compares with the one on 5 elements, in the cases* $\varepsilon = 10^{-5}, \mu = 10^{-3}$ *and* $\varepsilon = 10^{-6}, \mu = 10^{-4}$.

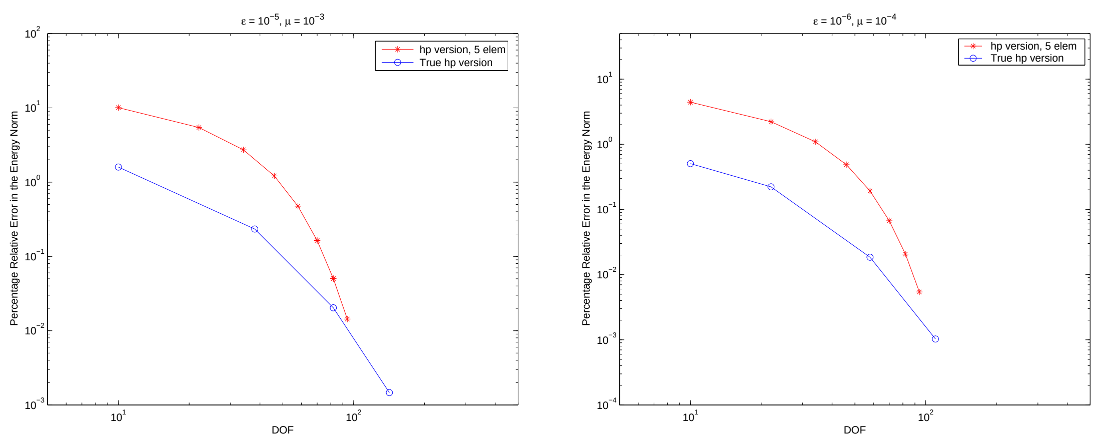

Figure 11: Energy norm convergence for the *hp* version with 5 elements and the true *hp* version.

Remark 3 *When the maximum norm is used as an error measure, the results are very similar to the ones shown before. Here, for completeness, we show in figure 12 a representative plot for the error given by*

$$\|\vec{u}_{EXACT} - \vec{u}_{FEM}\|_{\infty,\Omega} = \max_{k=1,2}\left\{\max_{[0,1]}|\vec{u}_{EXACT} - \vec{u}_{FEM}|\right\}, \tag{23}$$

versus the number of degrees of freedom, N*, for the case* $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ *and* $\mu = 0.01$ *– for other values of these parameters the results are similar. The slopes of the lines in figure 12 are approximately equal to the ones in figure 8. It is interesting, but not surprising, to note that when (23) is used as an error*

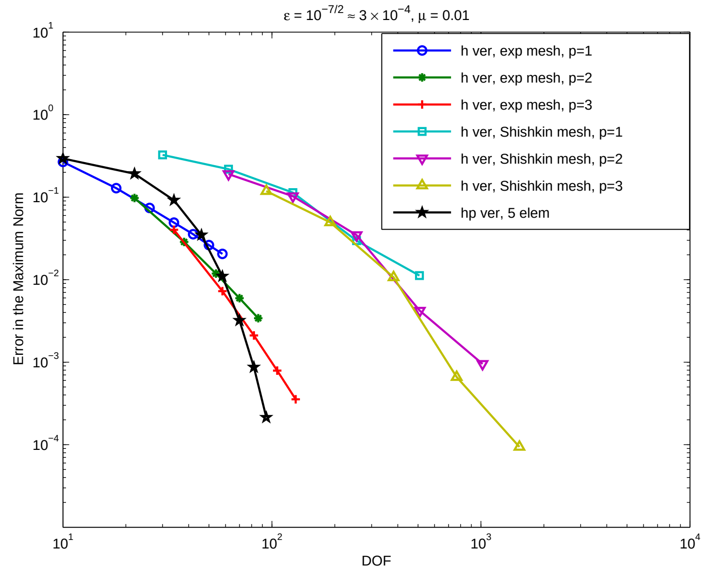

Figure 12: Maximum norm convergence for $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ and $\mu = 0.01$.

measure, the performance of the hp version does not improve as $\varepsilon, \mu \to 0$, as was the case when the energy norm was used to measure the error. This is shown in figure 13, and is due to the fact that from (21) and the interpolation inequality

$$\|v\|_{\infty,\Omega} \leq 2 \|v\|_{0,\Omega}^{1/2} \|v'\|_{0,\Omega}^{1/2},$$

one can obtain an error estimate for the error in the maximum norm in which the positive powers of ε and μ will not be present (see [24] for more details).

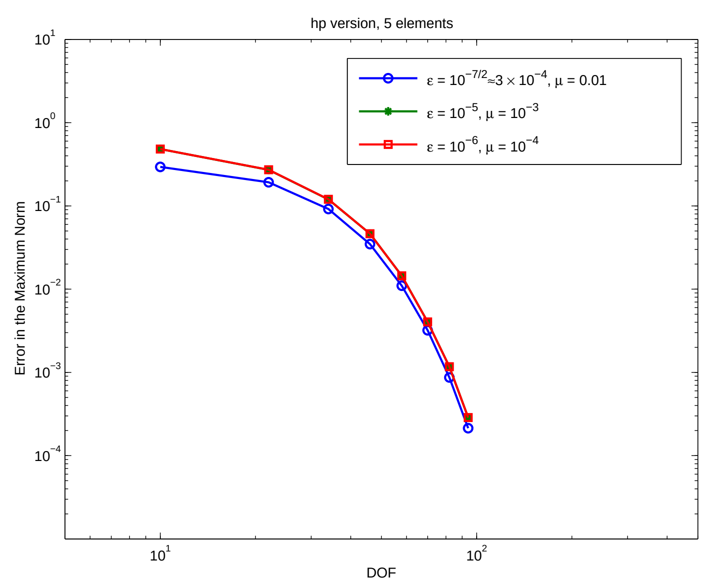

Figure 13: Maximum norm convergence for the *hp* version.

Lastly, we wish to see how the methods perform in the case $\mu = 1$, i.e. when we approximate the solution to the scalar fourth order singularly perturbed problem studied in [16]. Figures 14 and 15 show the energy norm convergence plot for the various FEMs, in the cases $\varepsilon = 10^{-3}, \mu = 1$ and $\varepsilon = 10^{-4}, \mu = 1$, respectively.

(For larger values of ε the h version on a uniform mesh and the p version on a single element perform reasonably well and the use of a non-uniform refinement is not as crucial, see, e.g., figure 4, while for smaller values of ε the results are similar to the ones shown here.) We should point out that since $\mu = 1$, the hp version considered now consists of only 3 elements (like in the scalar case, cf. (18)).

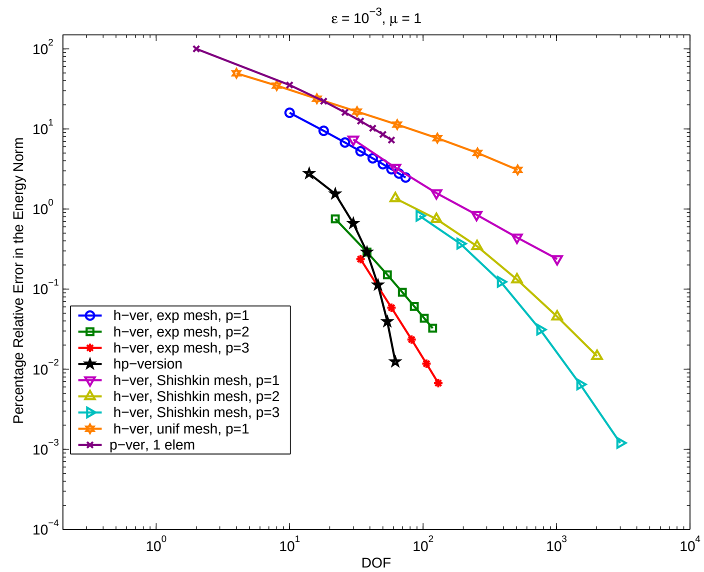

Figure 14: Energy norm convergence for $\varepsilon = 10^{-3}$ and $\mu = 1$.

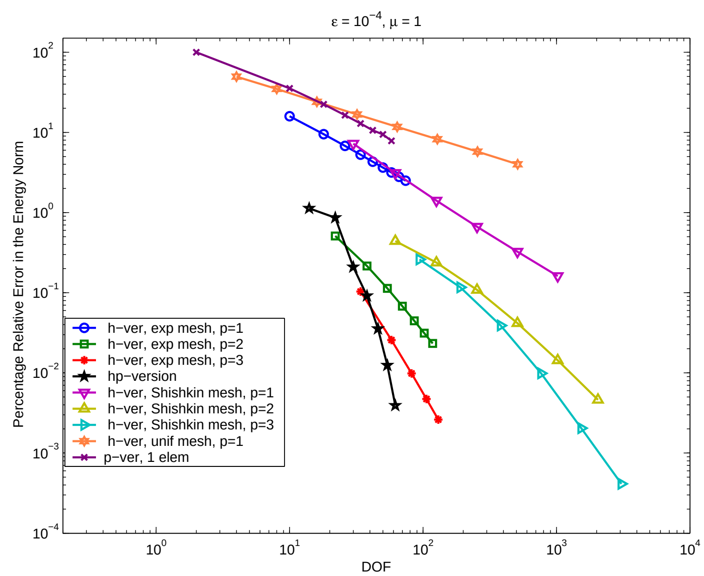

Figure 15: Energy norm convergence for $\varepsilon = 10^{-4}$ and $\mu = 1$.

From these figures we see that the performance of each method does not change significantly when $\mu = 1$, i.e. the h version on the uniform mesh and the p version on 1 element are not robust, while the h version on the Shishkin and exponential meshes, as well as the hp version are robust and behave in the same way they did for the values of μ considered earlier. (The slope of each line in figures 14 and 15 is almost identical to the ones in figure 8). There is, however, one exception: when $p = 1$, the h version on the exponential and Shishkin meshes converges at the same rate as it did before but the errors obtained are visibly higher (compare, e.g., figures 14 and 15 with figure 8). We believe that this is due to the fact that the same (non-uniform) mesh is used for the approximation of both components of $\vec{u} = [u_1(x), u_2(x)]^T$, while $u_2(x)$ is smooth with no boundary layers and a non-uniform mesh may not be the "best" choice. This does not happen when the polynomial degree is $p = 2$ or 3, and we believe that this is due to the better approximation properties that higher order polynomials possess. We do not wish to dwell on this issue, since after all the behavior of all the robust methods is quite satisfactory.

4.2 The variable coefficient case

Next, we consider the variable coefficient case, in which

$$A = \begin{bmatrix} 2\,(x+1)^2 & -\left(1+x^2\right) \\ -2\cos(\pi x/4) & 2.2e^{1-x} \end{bmatrix}, \vec{f}(x) = \begin{bmatrix} 2e^x \\ 10x+1 \end{bmatrix}, \vec{u}(0) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

An exact solution is not available, and for our computations we use a reference solution obtained with polynomials of degree 8 on the exponentially graded mesh (19), supplemented with a uniform refinement of $N/3$ elements in the middle of the domain (see figure 16). Since this is a variable coefficient problem with non-constant right-hand side, the addition of the uniform refinement is necessary in order for all the components of the solution to be accurately approximated. Hence, in our computations we add this uniform refinement to the exponential mesh as well, and we refer to it as a "modified exponential mesh".

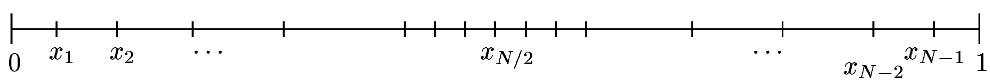

Figure 16: Modified exponential mesh.

We are again interested in the (now estimated) percentage relative error in the energy and maximum norms. However, given the results obtained for the constant coefficient case, we now focus our attention only on the methods which are converging uniformly in ε and μ, namely:

- The *hp* version on the 5 element (variable) mesh given by (20).
- The h version on a Shishkin mesh, with $p = 1, 2$ and 3.
- The h version on the modified exponential mesh, with $p = 1, 2$ and 3.

Figures 17 and 18 show the energy norm convergence of the above three methods for $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}, \mu = 0.01$ and $\varepsilon = 10^{-5}, \mu = 10^{-3}$, respectively. The results are almost identical to the constant coefficient case and they indicate, once more, the robust algebraic convergence rates for the h versions and the exponential convergence rate for the *hp* version.

In figure 19 we show the *hp* version on the 5 element mesh, for different values of ε and μ, and we observe that the positive powers of ε and μ in the error estimate (21) are present in the variable coefficient case as well, when the error is measured in the energy norm.

The performance of the robust FEMs when the error is measured in the maximum norm is shown in figure 20, which corresponds to $\varepsilon = 10^{-6}$ and $\mu = 10^{-4}$. As in the constant coefficient case, the situation does not change with the error measure, and all of the observations made in the previous subsection carry over to the variable coefficient case.

Finally, we consider the cases $\varepsilon = 10^{-3}, \mu = 1$ and $\varepsilon = 10^{-4}, \mu = 1$, which correspond to the scalar fourth order singularly perturbed problem [16]. Figures 21 and 22 show the performance of the robust methods: the results are almost identical as in the previous example, and qualitatively the same as all other values of ε and μ we have considered in this work.

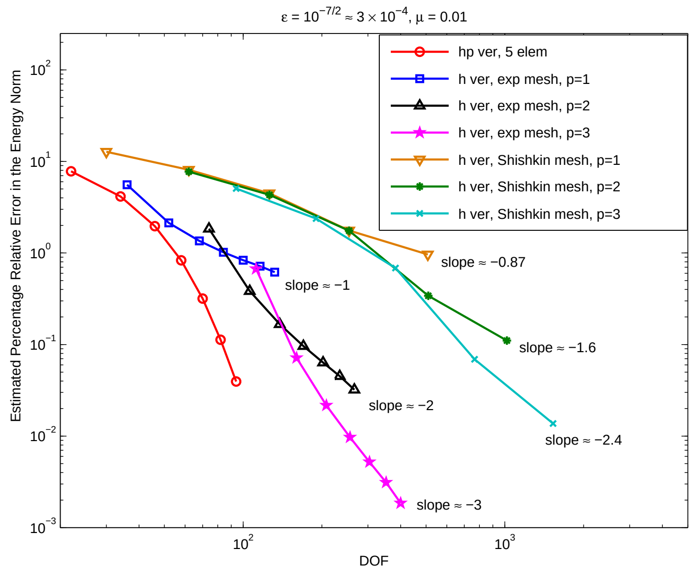

Figure 17: Energy norm convergence for $\varepsilon = 10^{-7/2} \approx 3 \times 10^{-4}$ and $\mu = 0.01$.

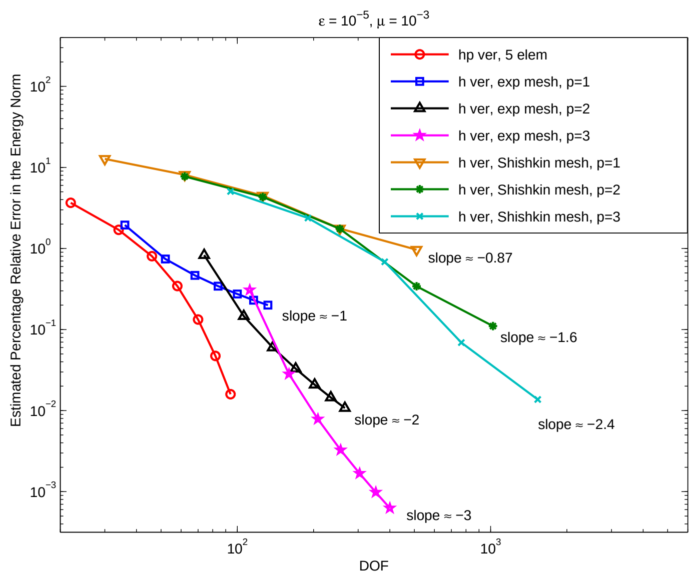

Figure 18: Energy norm convergence for $\varepsilon = 10^{-5}$ and $\mu = 10^{-3}$.

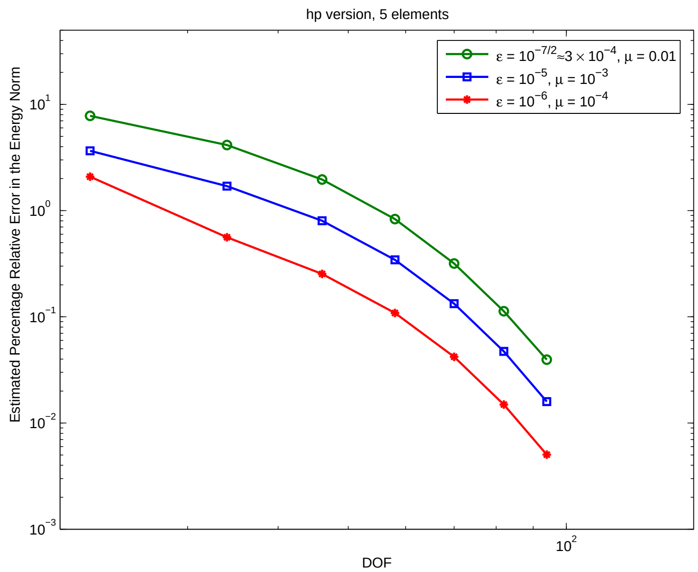

Figure 19: Energy norm convergence for the *hp* version.

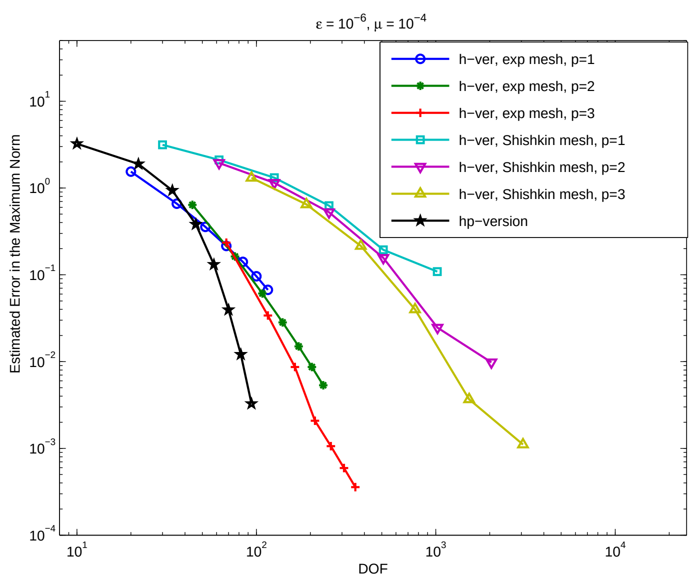

Figure 20: Maximum norm convergence for $\varepsilon = 10^{-6}$ and $\mu = 10^{-4}$.

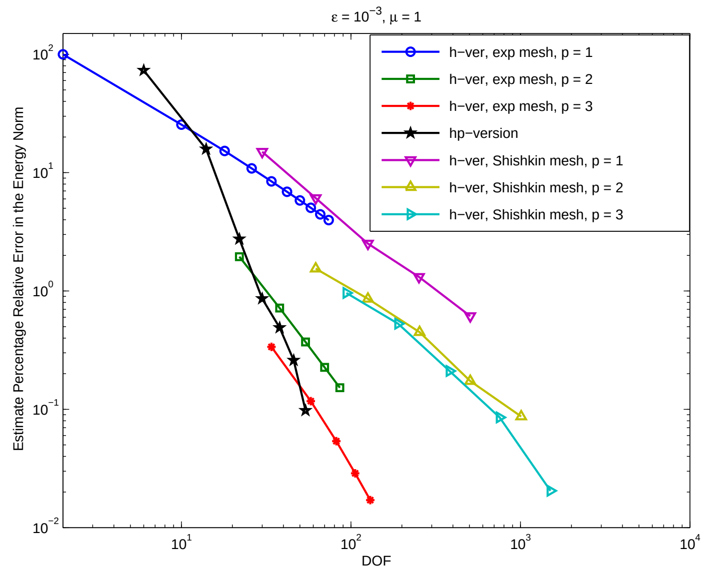

Figure 21: Energy norm convergence for $\varepsilon = 10^{-3}$ and $\mu = 1$.

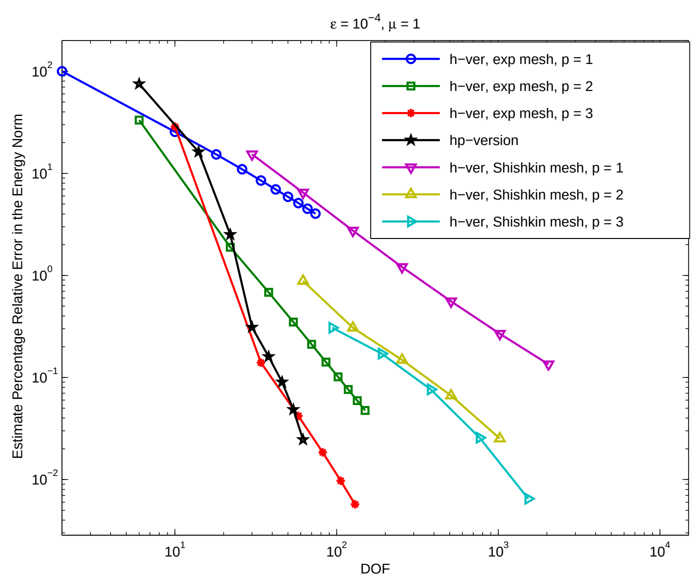

Figure 22: Energy norm convergence for $\varepsilon = 10^{-4}$ and $\mu = 1$.

5 Conclusions

We have studied the finite element approximation of systems of singularly perturbed reaction-diffusion problems by various versions of the FEM. For the model problem under consideration, we have demonstrated numerically how the h version on a uniform mesh and the p version on a single element do not converge uniformly, as $\varepsilon, \mu \to 0$, while the h version on either a Shishkin or an exponentially graded mesh, is robust and its performance does not deteriorate as $\varepsilon, \mu \to 0$. In particular, when the h version is used with polynomials of degree p on a Shishkin mesh, we observe $O\left(\left(N^{-1}\ln N\right)^p\right)$ convergence, and when the same method is used on the exponentially graded mesh, the logarithmic term is no longer present and the optimal $O\left(N^{-p}\right)$ convergence rate is observed. We also proposed an hp scheme on a 5 element variable mesh which converges uniformly in ε and μ at an exponential rate.

The above remarks are valid when the error is measured in the energy and maximum norms, and for the range of values $0 < \varepsilon \leq \mu \leq 1$, including the case $\mu = 1$ which corresponds to the scalar fourth order singularly perturbed problem.

The numerical analysis of the proposed hp scheme, and the proof of the observed exponential rate of convergence is carried out in [24].

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