

Multilevel QMC with Product Weights for Affine-Parametric, Elliptic PDEs

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Multilevel QMC with Product Weights for Affine-Parametric, Elliptic PDEs

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Abstract We present an error analysis of higher order Quasi-Monte Carlo (QMC) integration and of randomly shifted QMC lattice rules for parametric operator equations with uncertain input data taking values in Banach spaces. Parametric expansions of these input data in locally supported bases such as splines or wavelets was shown in [R.N. Gantner, L. Herrmann, and Ch. Schwab, Quasi-Monte Carlo integration for affine-parametric, elliptic PDEs: local supports imply product weights, Report 2016-32, Seminar for Applied Mathematics, ETH Zürich] to allow for dimension independent convergence rates of combined QMC-Galerkin approximations. In the present work, we review and refine the results in that reference to the multilevel setting, along the lines of [F.Y. Kuo, Ch. Schwab, and I.H. Sloan: Multi-level Quasi-Monte Carlo Finite Element Methods for a Class of Elliptic PDEs with Random Coefficients, *Journ. Found. Comp. Math.* **15**(2) 441-449 (2015)] where randomly shifted lattice rules and globally supported representations were considered, and also the results of [J. Dick, F.Y. Kuo, Q.T. LeGia, and Ch. Schwab: Multi-level higher order QMC Galerkin discretization for affine parametric operator equations, *SIAM J. Numer. Anal.*, 54/4 (2016), pp. 2541-2568] in the particular situation of locally supported bases in the parametrization of uncertain input data. In particular, we show that locally supported basis functions allow for multilevel QMC quadrature with product weights, and prove new error vs. work estimates superior to those in these references (albeit at stronger, mixed regularity assumptions on the parametric integrand functions than what was required in the single-level QMC error analysis in the first reference above). Numerical experiments on a model affine parametric elliptic problem confirm the analysis.

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1 Introduction

A core task in computational uncertainty quantification (computational UQ for short) is to approximate the statistics of (functionals of) solution to partial differential equations (PDEs for short) which depend on parameters describing uncertain input data. Upon placing measures on the set of admissible parameters, the computation of mathematical expectations in so-called *forward UQ* and in *Bayesian inverse UQ* of such PDEs on possibly large sets of data amounts to a problem of *high dimensional numerical integration*; we refer to the surveys [23, 4, 3] and the references there for details.

In the present note, we address the numerical analysis of high-dimensional numerical integrations methods of *Quasi Monte-Carlo* (QMC for short) type for the efficient numerical approximation of expectations of solutions of parametric PDEs over high-dimensional parameter spaces. Pioneering contributions to the mathematical foundation of dimension-independent convergence rates for QMC quadrature methods for such problems, that also the present note will draw on, have been made by I. H. Sloan and H. Woźniakowski in [26], after earlier, foundational work by I. H. Sloan and S. Joe in [24].

Specifically, we consider the linear, affine-parametric elliptic PDE

$$-\nabla \cdot (a(x, \mathbf{y}) \nabla u(x, \mathbf{y})) = f(x) \text{ in } D, \quad u(x, \mathbf{y}) \Big|_{\partial D} = 0, \quad (1)$$

with parametrized input $a(x, \mathbf{y})$.

The domain $D \subset \mathbb{R}^d$, $d = 1, 2$, is a polygon with straight sides or an interval. Specifically, QMC rules with *product weights* are considered which are known to have linear complexity in the integration dimension, cp. [21, 22]. To prove error versus work bounds of these algorithms, with explicit estimation of constants on the dimension s of integration, and of the form $\mathcal{O}(\varepsilon^{-\theta})$, $\theta > 0$, for a given accuracy $\varepsilon > 0$ is the purpose of the present paper.

Convergence analysis of QMC methods with randomly shifted lattice rules applied to a parametric PDE of the type of (1) was first established in [19] together with the survey [18]. Randomly shifted lattice rules were first proposed in [25]. A multilevel version for parametric PDEs was first analyzed in [20]. This theory was extended in [5, 6] with interlaced polynomial lattice rules, which achieve higher order convergence rates which are independent of the dimension s of the domain of integration. Conditions for such dimension independent error bounds of QMC algorithms were first shown in the seminal work [26] for integrand functions belonging to certain weighted function spaces with so-called *product weights*. In [18], analogous results were shown to hold for randomly shifted lattice rules, and for input parametrizations in terms of globally supported basis functions (as, e.g., Karhunen-Loève expansions) with so-called *product and order (POD) dependent weights*. General references for QMC integration are [18, 7]; see also the survey [13] for multilevel Monte Carlo methods.

As in the mentioned references, we admit parameter vectors $\mathbf{y} = (y_j)_{j \geq 1}$ whose components take values in the closed interval $[-\frac{1}{2}, \frac{1}{2}]$, i.e., we will consider

$$\mathbf{y} \in U := \left[-\frac{1}{2}, \frac{1}{2} \right]^{\mathbb{N}}.$$

We model uncertainty in diffusion coefficients $a(x, \mathbf{y})$ to the PDE (1) by assuming that the parameter vectors to be independent, identically distributed (i.i.d.) with respect to the uniform product probability measure

$$\mu(d\mathbf{y}) := \bigotimes_{j \geq 1} dy_j.$$

The triplet $(U, \bigotimes_{j \geq 1} \mathcal{B}([-1/2, 1/2]), \mu)$ is a probability space. For any Banach space B , the mathematical expectation of F with respect to the probability measure μ is a Bochner integral of the strongly measurable, integrable map $F : U \rightarrow B$ which will be denoted by

$$\mathbb{E}(F) := \int_U F(\mathbf{y}) \mu(d\mathbf{y}). \quad (2)$$

The parametric input $a(x, \mathbf{y})$ of (1) is assumed to be of the form

$$a(x, \mathbf{y}) = \bar{a}(x) + \sum_{j \geq 1} y_j \psi_j(x), \quad \text{a.e. } x \in D, \mathbf{y} \in U, \quad (3)$$

where $\{\bar{a}, \psi_j : j \geq \mathbb{N}\} \subset L^\infty(D)$ and \bar{a} is such that $0 < \bar{a}_{\min} \leq \bar{a}_{\max}$ exist and satisfy

$$\bar{a}_{\min} \leq \text{ess inf}_{x \in D} \{\bar{a}(x)\} \leq \text{ess sup}_{x \in D} \{\bar{a}(x)\} \leq \bar{a}_{\max}.$$

Convergence analysis for QMC with product weights was recently carried out in [10] under the assumption that there exists $\kappa \in (0, 1)$ and a sequence $(b_j)_{j \geq 1} \in (0, 1]^{\mathbb{N}}$ such that

$$\left\| \frac{\sum_{j \geq 1} |\psi_j|/b_j}{2\bar{a}} \right\|_{L^\infty(D)} \leq \kappa < 1. \quad (\mathbf{A1})$$

A (dimension independent) convergence rate of $1/p$ in terms of the number of QMC points for the approximate evaluation of (2) was shown in [10, Section 6] if $(b_j)_{j \geq 1} \in \ell^p(\mathbb{N})$ for the range $p \in (0, 2]$. These rates coincide, in the mentioned range of summability exponents, with the convergence rates of best N -term approximation rates of generalized polynomial chaos expansions obtained in [2, Theorem 1.2 and Equation (11)]. As in [2], the assumption in **(A1)** can accommodate possible localization in D of the supports of the function system $(\psi_j)_{j \geq 1}$.

For every parameter instance $\mathbf{y} \in U$, in the physical domain D a standard, first order accurate Galerkin Finite Element (FE for short) discretization of the parametric PDE (1) will be applied. In the polygonal domain D , first order FEM based on sequences of uniformly refined, regular simplicial meshes are well known to converge at suboptimal rates due to *corner singularities* in the solution, even if $a(x, \mathbf{y})$ and f in (1) are smooth. To establish full FE convergence rates on locally refined meshes

coupled with the QMC error estimates, parametric regularity estimates in *Kondrat'ev* spaces will be demonstrated.

In Section 2 well-posedness of the parametric solution and approximation by dimension truncation and FE is discussed. Particular weighted Sobolev spaces of parametric regularity that are required for the error analysis of multilevel QMC and general error estimates are reviewed in Section 3. Parametric regularity estimates of the dimension truncation and FE error are proven in Section 4. These estimates yield error bounds of multilevel QMC algorithms that are demonstrated in Section 5. In Section 6, parameter choices are derived that minimize the needed work for a certain error threshold. As a numerical experiment, we analyze a piecewise linear wavelet basis to expand the diffusion coefficient in one spatial dimension. The experiment confirms the theory and also shows that the multilevel QMC algorithm beats the single-level version comparing the needed work against the achieved accuracy.

2 Well-posedness and spatial approximation

The parametric problem in (1) admits a symmetric variational formulation with trial and test space $V := H_0^1(D)$, with dual space denoted by $V^* = H^{-1}(D)$. Let $f \in V^*$ and let the assumption in **(A1)** be satisfied. Then the *parametric weak formulation* of (1) reads: For every $\mathbf{y} \in U$ find $u(\cdot, \mathbf{y}) \in V$ such that

$$\int_D a(\cdot, \mathbf{y}) \nabla u(\cdot, \mathbf{y}) \cdot \nabla v dx = f(v), \quad \forall v \in V. \quad (4)$$

Since the assumption in **(A1)** implies that

$$0 < (1 - \kappa) \bar{a}_{\min} \leq \operatorname{ess\,inf}_{x \in D} \{a(x, \mathbf{y})\}, \quad \mathbf{y} \in U,$$

and

$$\operatorname{ess\,sup}_{x \in D} \{a(x, \mathbf{y})\} \leq (1 + \kappa) \bar{a}_{\max}, \quad \mathbf{y} \in U,$$

the parametric bilinear form $(w, v) \mapsto \int_D a(\mathbf{y}) \nabla w \cdot \nabla v dx$ is continuous and coercive on $V \times V$, uniformly with respect to the parameter $\mathbf{y} \in U$. By the Lax–Milgram lemma the unique solution $u(\cdot, \mathbf{y}) \in V$ to (4) exists, is a strongly measurable mapping from U to V (by the second Strang lemma), and satisfies the apriori estimate

$$\|u(\cdot, \mathbf{y})\|_V \leq \frac{\|f\|_{V^*}}{(1 - \kappa) \bar{a}_{\min}}, \quad \mathbf{y} \in U.$$

A finite dimensional domain of integration for the use of QMC is achieved by truncating the expansion of $a(x, \mathbf{y})$ to $s \in \mathbb{N}$ terms. We introduce the notation that for every $\mathbf{y} \in U$, $\mathbf{y}_{\{1:s\}}$ is such that $(\mathbf{y}_{\{1:s\}})_j = y_j$ if $j \leq s$ and 0 otherwise, where $\{1:s\}$ denotes the set $\{1, \dots, s\}$. Specifically, for every $s \in \mathbb{N}$ define

$$u^s(\cdot, \mathbf{y}) := u(\cdot, \mathbf{y}_{\{1:s\}}), \quad \mathbf{y} \in U.$$

Proposition 1 ([10, Proposition 8]). *Let the assumption in (A1) be satisfied for some $\kappa \in (0, 1)$. If for some $s \in \mathbb{N}$*

$$\frac{\kappa \bar{a}_{\max}}{(1 - \kappa) \bar{a}_{\min}} \max_{j \geq s+1} \{b_j\} < 1,$$

then there exists a constant $C > 0$ such that for every $G(\cdot) \in V^$*

$$|\mathbb{E}(G(u)) - \mathbb{E}(G(u^s))| \leq C \|G(\cdot)\|_{V^*} \|f\|_{V^*} \left(\max_{j \geq s+1} \{b_j\} \right)^2.$$

For the study of the spatial regularity of $u(\mathbf{y})$ we consider weighted Sobolev spaces of *Kondrat'ev* type, which allow for full regularity shifts in polygonal domains $D \subset \mathbb{R}^2$ cp. [1]. In our setting the domain D is either a polygon in \mathbb{R}^2 with corners $\{c_1, \dots, c_J\}$ or an interval. To introduce weighted Sobolev spaces, we define the functions $r_i(x) := |x - c_i|$, $x \in D$, $i = 1, \dots, J$, where $|\cdot|$ denotes the Euclidean norm. For a J -tuple $\boldsymbol{\beta} = (\beta_1, \dots, \beta_J)$ with $\beta_i \in [0, 1)$, $i = 1, \dots, J$, we define the weight function $\Phi_{\boldsymbol{\beta}}$ by

$$\Phi_{\boldsymbol{\beta}}(x) := \prod_{i=1}^J r_i^{\beta_i}(x), \quad x \in D.$$

For multi-indices $\boldsymbol{\alpha} \in \mathbb{N}_0^2$, define the notation $\partial_x^{\boldsymbol{\alpha}} := \partial^{|\boldsymbol{\alpha}|} / (\partial x_1^{\alpha_1} \partial x_2^{\alpha_2})$. We define the weighted spaces $L_{\boldsymbol{\beta}}^2(D)$ and $H_{\boldsymbol{\beta}}^2(D)$ as the completion of $C^\infty(\bar{D})$ with respect to the following norms

$$\|v\|_{L_{\boldsymbol{\beta}}^2(D)} := \|v \Phi_{\boldsymbol{\beta}}\|_{L^2(D)} \quad (5)$$

and $\|v\|_{H_{\boldsymbol{\beta}}^2(D)}$ is given by

$$\|v\|_{H_{\boldsymbol{\beta}}^2(D)}^2 := \|v\|_{H^1(D)}^2 + \sum_{|\boldsymbol{\alpha}|=2} \|\partial_x^{\boldsymbol{\alpha}} v \Phi_{\boldsymbol{\beta}}\|_{L^2(D)}^2.$$

In the corresponding weighted Sobolev spaces, there is a full regularity shift of the Laplacian, cp. [1, Theorem 3.2], i.e., there exists a constant $C > 0$ such that for every $w \in V$ satisfying $\Delta w \in L_{\boldsymbol{\beta}}^2(D)$ there holds

$$\|w\|_{H_{\boldsymbol{\beta}}^2(D)} \leq C \|\Delta w\|_{L_{\boldsymbol{\beta}}^2(D)}. \quad (6)$$

where $\beta_i > 1 - \pi/\omega_i$ and $\beta_i \geq 0$, where ω_i denotes the interior angle of the corner c_i , $i = 1, \dots, J$. Hence, in the case that the domain D is convex, we choose $\boldsymbol{\beta} = (0, \dots, 0)$. There holds an approximation property in FE spaces in D with local mesh refinement towards the corners of D . To state it, let $\{\mathcal{T}_\ell\}_{\ell \geq 0}$ be a sequence of regular, simplicial triangulations of the polytope D , which can be generated either by judicious mesh grading in a vicinity of each corner of D cp. [1, Section 4] or by *newest vertex bisection*, cp. [12]. Let $V_\ell := \{v \in V : v|_K \in \mathbb{P}_1(K), K \in \mathcal{T}_\ell\}$, $\ell \geq 0$, where $\mathbb{P}_1(K)$

denotes the affine functions on K . The FE space V_ℓ is of finite dimension $M_\ell := \dim(V_\ell)$, $\ell \geq 0$. Then, there exists a constant $C > 0$ such that for every $w \in H_{\beta}^2(D)$ and every $\ell \geq 0$ there exists $w_\ell \in V_\ell$

$$\|w - w_\ell\|_V \leq CM_\ell^{-1/d} \|w\|_{H_{\beta}^2(D)}, \quad (7)$$

where $d = 1, 2$ is the dimension of the domain D . For $d = 2$, and in the case of graded meshes, this follows, for example, from [1, Lemmas 4.1 and 4.5]. An approximation property of this kind for nearest vertex bisection is shown in [12]. The regularity shift in (6) and the approximation property in (7) also hold if D is an interval (for $d = 1$).

Assume that the right hand side $f \in L_{\beta}^2(D)$, and that $\{|\nabla \bar{a}| \Phi_{\beta}, |\nabla \psi_j| \Phi_{\beta} : j \geq 1\} \subset L^\infty(D)$, and that there exists a bounded, positive sequence $(\bar{b}_j)_{j \geq 1}$, which satisfies

$$\left\| \left(|\nabla \bar{a}| + \sum_{j \geq 1} \frac{|\nabla \psi_j|}{\bar{b}_j} \right) \Phi_{\beta} \right\|_{L^\infty(D)} =: K < \infty. \quad (\text{A2})$$

This assumption readily implies that $\sup_{\mathbf{y} \in U} \{ \|\nabla a(\cdot, \mathbf{y})\| \Phi_{\beta} \|_{L^\infty(D)} \} < \infty$. As a consequence, $|\nabla a(\cdot, \mathbf{y})| \in L^\infty(\tilde{D})$ and $\Delta u(\cdot, \mathbf{y}) \in L^2(\tilde{D})$ for every compactly included subset $\tilde{D} \subset\subset D$ and $\mathbf{y} \in U$. Then, by the divergence theorem and by the product rule for every $v \in C_0^\infty(D)$

$$\begin{aligned} \int_D a(\cdot, \mathbf{y}) \nabla u(\cdot, \mathbf{y}) \cdot \nabla v \, dx &= - \int_D [\nabla \cdot (a(\cdot, \mathbf{y}) \nabla u(\cdot, \mathbf{y}))] v \, dx \\ &= - \int_D (a(\cdot, \mathbf{y}) \Delta u(\cdot, \mathbf{y}) + \nabla a(\cdot, \mathbf{y}) \cdot \nabla u(\cdot, \mathbf{y})) v \, dx. \end{aligned}$$

We have to show that $\Delta u(\mathbf{y}) \in L_{\beta}^2(D)$. By duality of the space $L_{\beta}^2(D)$, the previous identity, and by the Cauchy–Schwarz inequality,

$$\begin{aligned} \|a(\cdot, \mathbf{y}) \Delta u(\cdot, \mathbf{y})\|_{L_{\beta}^2(D)} &= \sup_{v \in L_{\beta}^2(D), \|v\|_{L_{\beta}^2(D)} \leq 1} \int_D a(\cdot, \mathbf{y}) \Delta u(\cdot, \mathbf{y}) v \Phi_{\beta}^2 \, dx \\ &= \sup_{v \in C_0^\infty(D), \|v\|_{L^2(D)} \leq 1} \int_D a(\cdot, \mathbf{y}) \Delta u(\cdot, \mathbf{y}) v \Phi_{\beta} \, dx \\ &= \sup_{v \in C_0^\infty(D), \|v\|_{L^2(D)} \leq 1} \int_D (f + \nabla a(\cdot, \mathbf{y}) \cdot \nabla u(\cdot, \mathbf{y})) v \Phi_{\beta} \, dx \\ &\leq \|f\|_{L_{\beta}^2(D)} + \|\nabla a(\cdot, \mathbf{y})\| \Phi_{\beta} \|u(\cdot, \mathbf{y})\|_V. \end{aligned} \quad (8)$$

Since $\text{ess inf}_{x \in D} \{a(x, \mathbf{y})\} \geq (1 - \kappa) \bar{a}_{\min}$, $\Delta u(\mathbf{y}) \in L_{\beta}^2(D)$. In (8), we applied that $C^\infty(D)$ is dense in $L_{\beta}^2(D)$ and used that the operator of pointwise multiplication $w \mapsto w \Phi_{-\beta}$ induces an isometric isomorphism from $L^2(D)$ to $L_{\beta}^2(D)$. W

The parametric FE solution is defined as the unique solution of the variational problem: for $\mathbf{y} \in U$ and $\ell \geq 0$, find $u^{\mathcal{T}_\ell}(\mathbf{y}) \in V_\ell$ such that

$$\int_D a(\cdot, \mathbf{y}) \nabla u^{\mathcal{T}_\ell}(\cdot, \mathbf{y}) \cdot \nabla v \, dx = f(v), \quad \forall v \in V_\ell. \quad (9)$$

Well-posedness of the parametric FE solution also follows by the Lax–Milgram lemma. As above, we define for every truncation level $s \in \mathbb{N}$ and $\ell \in \mathbb{N}_0$

$$u^{s, \mathcal{T}_\ell}(\cdot, \mathbf{y}) := u^{\mathcal{T}_\ell}(\cdot, \mathbf{y}_{\{1:s\}}), \quad \mathbf{y} \in U.$$

By Céa’s lemma, an Aubin–Nitsche argument, Proposition 1, (6), (7), and (8), there exists a constant $C > 0$ such that for every $s \in \mathbb{N}$, $\ell \geq 0$, and every $G(\cdot) \in L_{\boldsymbol{\beta}}^2(D)$,

$$\begin{aligned} |\mathbb{E}(G(u)) - \mathbb{E}(G(u^{s, \mathcal{T}_\ell}))| &\leq C \|G(\cdot)\|_{V^*} \|f\|_{V^*} \left(\max_{j \geq s+1} \{b_j\} \right)^2 \\ &\quad + C \|G(\cdot)\|_{L_{\boldsymbol{\beta}}^2(D)} \|f\|_{L_{\boldsymbol{\beta}}^2(D)} (M_\ell)^{-2/d}. \end{aligned} \quad (10)$$

Remark 1. If f and $G(\cdot)$ have less regularity, say $f \in (V^*, L_{\boldsymbol{\beta}}^2(D))_{t, \infty}$ and $G(\cdot) \in (V^*, L_{\boldsymbol{\beta}}^2(D))_{t', \infty}$, $t, t' \in [0, 1]$, the estimate in (10) holds with $M_\ell^{-(t+t')/d}$. This follows by interpolation. The interpolation spaces are in the sense of the *K-method*, cp. [27]. Since $L_{\boldsymbol{\beta}}^2(D) \subset V^*$ continuously which follows by the Hardy inequality, V^* and $L_{\boldsymbol{\beta}}^2(D)$ is an interpolation couple. Naturally the embedding $H^{-1+t'}(D) = (V^*, L^2(D))_{t', 2} \subset (V^*, L_{\boldsymbol{\beta}}^2(D))_{t', \infty}$ is continuous, since $L^2(D)$ is continuously embedded in $L_{\boldsymbol{\beta}}^2(D)$.

3 Multilevel QMC integration

Randomly shifted lattice rules and interlaced polynomial lattice rule are QMC rules that have well known *worst case error estimates* in particular weighted Sobolev spaces of regularity with respect to the dimensionally truncated parameter vectors $\mathbf{y}_{\{1:s\}}$, $s \in \mathbb{N}$. Generally, these QMC rules approximate dimensionally truncated integrals

$$I_s(F) := \int_{[-\frac{1}{2}, \frac{1}{2}]^s} F(\mathbf{y}) \, d\mathbf{y}.$$

Denote by $Q_{s, N}^{\text{RS}}(\cdot)$ and $Q_{s, N}^{\text{IP}}(\cdot)$ randomly shifted lattice rules and interlaced polynomial lattice rules in s dimension with N points, respectively. If the superscript is omitted both of the QMC rules are meant. For sequences $(s_\ell)_{\ell \geq 0}$ of truncation dimensions and numbers of QMC points $(N_\ell)_{\ell \geq 0}$, and for the meshes $\{\mathcal{T}_\ell\}_{\ell \geq 0}$ from Section 2, the multilevel QMC quadrature for $L \in \mathbb{N}$ levels is, for every $G \in V^*$, defined by

$$Q_L(G(u^L)) := \sum_{\ell=0}^L Q_{s_\ell, N_\ell}(G(u^\ell - u^{\ell-1})),$$

where we introduced the notation $u^\ell := u^{s_\ell, \mathcal{T}_\ell}$, $\ell \in \mathbb{N}_0$, and have set $u^{-1} := 0$. For the error analysis, we introduce for a sequence of QMC weights $\boldsymbol{\gamma} = (\gamma_u)_{u \subset \mathbb{N}}$ the weighted Sobolev spaces $\mathcal{W}_{s, \boldsymbol{\gamma}}$ and $\mathcal{W}_{s, \alpha, \boldsymbol{\gamma}, q, r}$ as closures of $C^\infty([-1/2, 1/2]^s)$ with respect to the norms

$$\|F\|_{\mathcal{W}_{s, \boldsymbol{\gamma}}} := \left(\sum_{u \subset \{1:s\}} \gamma_u^{-1} \int_{[-\frac{1}{2}, \frac{1}{2}]^{|u|}} \left| \int_{[-\frac{1}{2}, \frac{1}{2}]^{s-|u|}} \partial_{\mathbf{y}}^u F(\mathbf{y}) d\mathbf{y}_{\{1:s\} \setminus u} \right|^2 d\mathbf{y}_u \right)^{1/2}$$

and for $2 \leq \alpha \in \mathbb{N}$, $q, r \in [1, \infty]$

$$\|F\|_{\mathcal{W}_{s, \alpha, \boldsymbol{\gamma}, q, r}} := \left(\sum_{u \subset \{1:s\}} \left(\gamma_u^{-q} \sum_{\mathbf{v} \subset u} \sum_{\boldsymbol{\tau}_{u \setminus \mathbf{v}} \in \{1:\alpha\}^{|\mathbf{u} \setminus \mathbf{v}|}} \int_{[-\frac{1}{2}, \frac{1}{2}]^{|\mathbf{v}|}} \left| \int_{[-\frac{1}{2}, \frac{1}{2}]^{s-|\mathbf{v}|}} \partial_{\mathbf{y}}^{(\boldsymbol{\alpha}, \boldsymbol{\tau}_{u \setminus \mathbf{v}}, \mathbf{0})} F(\mathbf{y}) d\mathbf{y}_{\{1:s\} \setminus \mathbf{v}} \right|^q d\mathbf{y}_{\mathbf{v}} \right)^{r/q} \right)^{1/r}$$

with the obvious modifications if q or r is infinite. Here, $(\boldsymbol{\alpha}_{\mathbf{v}}, \boldsymbol{\tau}_{u \setminus \mathbf{v}}, \mathbf{0}) \in \{0:\alpha\}^s$ denotes a multi-index such that $(\boldsymbol{\alpha}_{\mathbf{v}}, \boldsymbol{\tau}_{u \setminus \mathbf{v}}, \mathbf{0})_j = \alpha$ for $j \in \mathbf{v}$, $(\boldsymbol{\alpha}_{\mathbf{v}}, \boldsymbol{\tau}_{u \setminus \mathbf{v}}, \mathbf{0})_j = \boldsymbol{\tau}_j$ for $j \in u \setminus \mathbf{v}$, and $(\boldsymbol{\alpha}_{\mathbf{v}}, \boldsymbol{\tau}_{u \setminus \mathbf{v}}, \mathbf{0})_j = 0$ for $j \notin u$, for every $u \subseteq \{1:s\}$, $\mathbf{v} \subseteq u$, $\boldsymbol{\tau} \in \{1:\alpha\}^{|\mathbf{u} \setminus \mathbf{v}|}$. Note that the integer $\alpha \geq 2$ is the interlacing factor. The following two estimates follow essentially from the worst case error estimates in [19, Theorem 2.1] and [5, Theorem 3.10] for $Q_{s,N}^{\text{RS}}(\cdot)$ and $Q_{s,N}^{\text{IP}}(\cdot)$, respectively. For every $\lambda \in (1/2, 1]$,

$$\begin{aligned} & \mathbb{E}^\Delta (|I_{s_L}(G(u^L)) - Q_L^{\text{RS}}(G(u^L))|^2) \\ & \leq \sum_{\ell=0}^L \left(\sum_{\emptyset \neq u \subset \{1:s_\ell\}} \gamma_u^\lambda \left(\frac{2\zeta(2\lambda)}{(2\pi^2)^\lambda} \right)^{|u|} \right)^{1/\lambda} (\varphi(N_\ell))^{-1/\lambda} \|G(u^\ell - u^{\ell-1})\|_{\mathcal{W}_{s_\ell, \boldsymbol{\gamma}}}^2, \end{aligned} \quad (11)$$

cp. [20, Equation (25)], where Δ denotes the random shift and φ denotes the Euler totient function. For every $\lambda \in (1/\alpha, 1]$,

$$\begin{aligned} & |I_{s_L}(G(u^L)) - Q_L^{\text{IP}}(G(u^L))| \\ & \leq \sum_{\ell=0}^L \left(\frac{2}{N_\ell - 1} \sum_{\emptyset \neq u \subset \{1:s_\ell\}} \gamma_u^\lambda (\rho_\alpha(\lambda))^{|u|} \right)^{1/\lambda} \|G(u^\ell - u^{\ell-1})\|_{\mathcal{W}_{s_\ell, \alpha, \boldsymbol{\gamma}, \infty, \infty}}, \end{aligned} \quad (12)$$

cp. [6, Equation (42)], where the constant $\rho_\alpha(\lambda)$ is finite if $\lambda > 1/\alpha$ as stated in [5, Equation (3.37)]. We remark that the choice of λ , α , $\boldsymbol{\gamma}$ in (11) and (12) may also depend on the level $\ell = 0, \dots, L$, which is not explicit in the notation.

4 Parametric regularity

As in the single level QMC analysis in [10], we introduce the parameter set $\tilde{U} = [-1, 1]^{\mathbb{N}}$ with elements $\mathbf{z} \in \tilde{U}$. Set $\eta \in (\kappa, 1)$. We split the sparsity of the sequence $(b_j)_{j \geq 1}$ between spatial approximation and QMC approximation rates, which naturally couple in multilevel integration methods. For a sequence $(\hat{b}_j)_{j \geq 1}$ (to be specified in the following) which satisfies the assumption **(A1)**, and for every $\mathbf{y} \in U$ define

$$\bar{a}_{\mathbf{y}}(x) = \bar{a}(x) + \sum_{j \geq 1} y_j \psi_j(x) \quad \text{and} \quad \psi_{\mathbf{y},j}(x) = \frac{\eta^{-1} - 2|y_j|}{2\hat{b}_j} \psi_j(x), \quad \text{a.e. } x \in D, j \in \mathbb{N}, \quad (13)$$

which are used to construct

$$\tilde{a}_{\mathbf{y}}(x, \mathbf{z}) := \bar{a}_{\mathbf{y}}(x) + \sum_{j \geq 1} z_j \psi_{\mathbf{y},j}(x), \quad \text{a.e. } x \in D, \mathbf{z} \in \tilde{U}.$$

We recall that for every $\mathbf{y} \in U$

$$\left\| \frac{\sum_{j \geq 1} |\psi_{\mathbf{y},j}|}{\bar{a}_{\mathbf{y}}} \right\|_{L^\infty(D)} \leq \frac{\kappa}{\eta} < 1, \quad (14)$$

which implies that the problem for arbitrary $\mathbf{y} \in U$ and $\mathbf{z} \in \tilde{U}$ to find $\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) \in V$ such that

$$\int_D \tilde{a}_{\mathbf{y}}(\cdot, \mathbf{z}) \nabla \tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) \cdot \nabla v \, dx = f(v), \quad \forall v \in V,$$

is well-posed, cp. [10, Section 4]. Then, the affine mapping $T_{\mathbf{y}} : \tilde{U} \rightarrow T_{\mathbf{y}}(\tilde{U}) \subset \mathbb{R}^{\mathbb{N}}$, which is given by

$$(T_{\mathbf{y}}(\mathbf{z}))_j := y_j + \frac{\eta^{-1} + 2|y_j|}{2\hat{b}_j} z_j, \quad j \geq 1, \mathbf{z} \in \tilde{U}, \quad (15)$$

yields by construction, cp. [10, Section 4], a connection of $u(\cdot, \mathbf{y})$ and $\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z})$, i.e.,

$$\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) = u(\cdot, T_{\mathbf{y}}(\mathbf{z})) \quad \text{in } V.$$

Finally, by the chain rule for every $\boldsymbol{\tau} \in \mathcal{F} := \{\boldsymbol{\tau}' \in \mathbb{N}_0^{\mathbb{N}} : |\boldsymbol{\tau}'| < \infty\}$

$$\partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) \Big|_{\mathbf{z}=\mathbf{0}} = \left(\prod_{j \geq 1} \left(\frac{\eta^{-1} - 2|y_j|}{2\hat{b}_j} \right)^{\tau_j} \right) \partial_{\mathbf{y}}^{\boldsymbol{\tau}} u(\cdot, \mathbf{y}). \quad (16)$$

The dilated coordinate is analogously applied to dimensionally truncated solution and the FE approximation, which are denoted by $\tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z})$, $\tilde{u}_{\mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})$, and $\tilde{u}_{\mathbf{y}}^{s, \mathcal{J}_\ell}(\cdot, \mathbf{z})$. As observed in [10, Theorems 10 and 12], this sequence $(\hat{b}_j)_{j \geq 1}$ will be the input for the product weights of the considered QMC rules and its summability properties will be

a sufficient condition to achieve a certain dimension-independent convergence rate of either type of QMC rule.

4.1 Dimensionally truncated differences

Let $s \in \mathbb{N}$ be the truncation of the series expansion of $a(\cdot, \mathbf{y})$ and also of $\tilde{a}_{\mathbf{y}}(\cdot, \mathbf{z})$. The difference of solutions with respect to the full resp. to the truncated expansion of the parametric coefficient satisfies

$$\int_D \tilde{a}_{\mathbf{y}}(\cdot, \mathbf{z}) \nabla (\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z})) \cdot \nabla v \, dx = - \int_D \sum_{j>s} z_j \psi_{\mathbf{y},j} \nabla \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) \cdot \nabla v \, dx, \quad \forall v \in V.$$

In this section we split the sequence $(b_j)_{j \geq 1}$ into two sequences by $b_j = b_j^{1-\theta} b_j^\theta$, $j \in \mathbb{N}$, $\theta \in [0, 1]$, and consider the dilated coordinate in (13) and (15) with respect to the sequence $(b_j^{1-\theta})_{j \geq 1}$, i.e., here $(\hat{b}_j)_{j \geq 1} = (b_j^{1-\theta})_{j \geq 1}$, which satisfies **(A1)** by the condition $b_j \in (0, 1]$, $j \in \mathbb{N}$. By the assumption in **(A1)** and (14), for every $\mathbf{y} \in U$,

$$\left\| \frac{\sum_{j \geq 1} |\psi_{\mathbf{y},j}| / b_j^\theta}{\bar{a}_{\mathbf{y}}} \right\|_{L^\infty(D)} \leq \frac{\kappa}{\eta} < 1. \quad (17)$$

Theorem 1. *Let the assumption in **(A1)** be satisfied. There exists a constant $C > 0$ such that for every $\mathbf{y} \in U$ and for every $s \in \mathbb{N}$*

$$\sum_{\boldsymbol{\tau} \in \mathcal{F}} \frac{1}{(\boldsymbol{\tau}!)^2} \left\| \partial_{\mathbf{z}}^{\boldsymbol{\tau}} (\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z})) \Big|_{\mathbf{z}=\mathbf{0}} \right\|_V^2 \leq C \|f\|_{V^*}^2 \sup_{j>s} \{b_j^{2\theta}\}.$$

Proof. As in the proof of [10, Lemma 3], we will consider the Taylor coefficients

$$t_{\mathbf{y},\boldsymbol{\tau}} := \frac{1}{\boldsymbol{\tau}!} \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) \Big|_{\mathbf{z}=\mathbf{0}} \quad \text{and} \quad t_{\mathbf{y},\boldsymbol{\tau}}^s := \frac{1}{\boldsymbol{\tau}!} \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) \Big|_{\mathbf{z}=\mathbf{0}}, \quad \forall \boldsymbol{\tau} \in \mathcal{F}. \quad (18)$$

We introduce a parametric energy norm $\|\cdot\|_{\bar{a}_{\mathbf{y}}}$ for every $\mathbf{y} \in U$ by

$$\|v\|_{\bar{a}_{\mathbf{y}}}^2 := \int_D \bar{a}_{\mathbf{y}} |\nabla v|^2 \, dx, \quad \forall v \in V.$$

Evidently, $t_{\mathbf{y},\boldsymbol{\tau}}^s = 0$ in case that $\tau_j > 0$ for some $j > s$. For every $\boldsymbol{\tau} \in \mathcal{F}$,

$$\begin{aligned} \int_D \bar{a}_{\mathbf{y}} \nabla (t_{\mathbf{y},\boldsymbol{\tau}} - t_{\mathbf{y},\boldsymbol{\tau}}^s) \cdot \nabla v \, dx &= - \sum_{j(\boldsymbol{\tau})} \int_D \psi_{\mathbf{y},j} \nabla (t_{\mathbf{y},\boldsymbol{\tau}-\mathbf{e}_j} - t_{\mathbf{y},\boldsymbol{\tau}-\mathbf{e}_j}^s) \cdot \nabla v \, dx \\ &\quad - \sum_{j(\boldsymbol{\tau}), j>s} \int_D \psi_{\mathbf{y},j} \nabla t_{\mathbf{y},\boldsymbol{\tau}-\mathbf{e}_j}^s \cdot \nabla v \, dx \quad \forall v \in V, \end{aligned}$$

where we used the notation $j(\boldsymbol{\tau}) := \{j \in \mathbb{N} : \tau_j > 0\}$. Testing with $v = t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s$, we find for $\mathbf{0} \neq \boldsymbol{\tau} \in \mathcal{F}$,

$$\begin{aligned} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2 &\leq \int_D \sum_{j(\boldsymbol{\tau})} |\psi_{\mathbf{y}, j}| |\nabla(t_{\mathbf{y}, \boldsymbol{\tau} - e_j} - t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^s)| |t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s| dx \\ &\quad + \int_D \sum_{j(\boldsymbol{\tau}), j > s} |\psi_{\mathbf{y}, j}| |t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^s| |t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s| dx, \end{aligned}$$

where $e_j \in \mathcal{F}$ is such that $(e_j)_i = 1$ if $j = i$ and zero otherwise. We obtain with a twofold application of the Cauchy–Schwarz inequality using (A1) and (17)

$$\begin{aligned} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2 &\leq \left(\frac{\kappa}{\eta} \int_D \sum_{j(\boldsymbol{\tau})} |\psi_{\mathbf{y}, j}| |\nabla(t_{\mathbf{y}, \boldsymbol{\tau} - e_j} - t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^s)|^2 dx \right)^{1/2} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}} \\ &\quad + \left(\frac{\kappa}{\eta} \sup_{j > s} \{b_j^\theta\} \int_D \sum_{j(\boldsymbol{\tau}), j > s} |\psi_{\mathbf{y}, j}| |t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^s|^2 dx \right)^{1/2} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}. \end{aligned}$$

Hence, by the Young inequality with $\varepsilon > 0$ and by (A1)

$$\begin{aligned} \sum_{k \geq 1} \sum_{|\boldsymbol{\tau}|=k} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2 &\leq (1 + \varepsilon) \frac{\kappa}{\eta} \sum_{k \geq 1} \int_D \sum_{|\boldsymbol{\tau}|=k-1} \sum_{j \geq 1} |\psi_{\mathbf{y}, j}| |\nabla(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s)|^2 dx \\ &\quad + \left(1 + \frac{1}{\varepsilon}\right) \frac{\kappa}{\eta} \sup_{j > s} \{b_j^\theta\} \sum_{k \geq 1} \int_D \sum_{|\boldsymbol{\tau}|=k-1} \sum_{j > s} |\psi_{\mathbf{y}, j}| |t_{\mathbf{y}, \boldsymbol{\tau}}^s|^2 dx \\ &\leq (1 + \varepsilon) \left(\frac{\kappa}{\eta}\right)^2 \sum_{k \geq 0} \sum_{|\boldsymbol{\tau}|=k} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2 \\ &\quad + \left(1 + \frac{1}{\varepsilon}\right) \left(\frac{\kappa}{\eta}\right)^2 \sup_{j > s} \{b_j^{2\theta}\} \sum_{k \geq 0} \sum_{|\boldsymbol{\tau}|=k} \|t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2. \end{aligned}$$

Since $\kappa < \eta$, we can choose ε such that $(1 + \varepsilon)(\kappa/\eta)^2 < 1$ and conclude that

$$\sum_{\boldsymbol{\tau} \in \mathcal{F}} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2 \leq 2 \|t_{\mathbf{y}, \mathbf{0}} - t_{\mathbf{y}, \mathbf{0}}^s\|_{\bar{a}_{\mathbf{y}}}^2 + \frac{1 + 1/\varepsilon}{1 - (1 + \varepsilon)(\kappa/\eta)^2} \sup_{j > s} \{b_j^{2\theta}\} \sum_{\boldsymbol{\tau} \in \mathcal{F}} \|t_{\mathbf{y}, \boldsymbol{\tau}}^s\|_{\bar{a}_{\mathbf{y}}}^2,$$

which implies the assertion with [10, Lemma 3 and Proposition 8] using that $b_j \in (0, 1]$, $j \in \mathbb{N}$. Note that [10, Lemma 3] gives an upper bound, since $\partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) = \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}_{\{1:s\}}}^s(\cdot, \mathbf{z})$ if $\tau_j = 0$ for every $j > s$ and $\partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) = 0$ otherwise. \square

Remark 2. The estimate in Theorem 1 also holds when the differences $\partial_{\mathbf{z}}^{\boldsymbol{\tau}} (\tilde{u}_{\mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^{s, \mathcal{J}_\ell}(\cdot, \mathbf{z}))|_{\mathbf{z}=\mathbf{0}}$, $\boldsymbol{\tau} \in \mathcal{F}$, $\ell \geq 0$, are considered and the constant is independent of $\{\mathcal{J}_\ell\}_{\ell \geq 0}$. Since only the variational formulation was used in the proof, the corresponding variational formulation with trial and test space V_ℓ can be used instead.

4.2 FE differences

We assume now that the sequence $(\bar{b}_j)_{j \geq 1}$ satisfies the assumptions in **(A1)** and in **(A2)**. We consider the dilated coordinate in (13) and (15) with respect to this sequence $(\bar{b}_j)_{j \geq 1}$, i.e., here $(\hat{b}_j)_{j \geq 1} = (\bar{b}_j)_{j \geq 1}$.

Proposition 2. *Let the assumption in **(A1)** and **(A2)** be satisfied for $(\bar{b}_j)_{j \geq 1}$. Then, there exists a constant $C > 0$ (independent of f) such that for every $\mathbf{y} \in U$*

$$\sum_{\boldsymbol{\tau} \in \mathcal{F}} \frac{1}{(\boldsymbol{\tau}!)^2} \left\| \Delta \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) \Big|_{\mathbf{z}=\mathbf{0}} \right\|_{L^2_{\boldsymbol{\beta}}(D)}^2 \leq C \|f\|_{L^2_{\boldsymbol{\beta}}(D)}^2.$$

Proof. Recall that the Taylor coefficients $\{t_{\mathbf{y}, \boldsymbol{\tau}} : \boldsymbol{\tau} \in \mathcal{F}\}$ have been defined in (18). We also recall that for any $\mathbf{0} \neq \boldsymbol{\tau} \in \mathcal{F}$,

$$\int_D \bar{a}_{\mathbf{y}} \nabla t_{\mathbf{y}, \boldsymbol{\tau}} \cdot \nabla v \, dx = - \sum_{j(\boldsymbol{\tau})} \int_D \psi_{\mathbf{y}, j} \nabla t_{\mathbf{y}, \boldsymbol{\tau} - e_j} \cdot \nabla v \, dx, \quad \forall v \in V.$$

Similarly as in Section 2, by the divergence theorem for every $v \in C_0^\infty(D)$

$$- \int_D \bar{a}_{\mathbf{y}} \Delta t_{\mathbf{y}, \boldsymbol{\tau}} v \, dx = \int_D \left(\nabla \bar{a}_{\mathbf{y}} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau}} + \sum_{j(\boldsymbol{\tau})} (\nabla \psi_{\mathbf{y}, j} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau} - e_j} + \psi_{\mathbf{y}, j} \Delta t_{\mathbf{y}, \boldsymbol{\tau} - e_j}) \right) v \, dx$$

Since $\Delta t_{\mathbf{y}, \boldsymbol{\tau}} \Phi_{\boldsymbol{\beta}} \in L^2(D)$, cp. (8), we may use $-\Delta t_{\mathbf{y}, \boldsymbol{\tau}} \Phi_{\boldsymbol{\beta}}^2$ as a test function and obtain with the Young inequality for any $\varepsilon > 0$

$$\begin{aligned} \int_D \bar{a}_{\mathbf{y}} |\Delta t_{\mathbf{y}, \boldsymbol{\tau}}|^2 \Phi_{\boldsymbol{\beta}}^2 \, dx &= - \int_D \left(\nabla \bar{a}_{\mathbf{y}} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau}} + \sum_{j(\boldsymbol{\tau})} \nabla \psi_{\mathbf{y}, j} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau} - e_j} \right) \Delta t_{\mathbf{y}, \boldsymbol{\tau}} \Phi_{\boldsymbol{\beta}}^2 \, dx \\ &\quad - \int_D \sum_{j(\boldsymbol{\tau})} \psi_{\mathbf{y}, j} \Delta t_{\mathbf{y}, \boldsymbol{\tau} - e_j} \Delta t_{\mathbf{y}, \boldsymbol{\tau}} \Phi_{\boldsymbol{\beta}}^2 \, dx \\ &\leq \varepsilon \int_D \bar{a}_{\mathbf{y}} |\Delta t_{\mathbf{y}, \boldsymbol{\tau}}|^2 \Phi_{\boldsymbol{\beta}}^2 \, dx \\ &\quad + \frac{1}{4\varepsilon} \int_D \frac{\Phi_{\boldsymbol{\beta}}^2}{\bar{a}_{\mathbf{y}}} \left(\nabla \bar{a}_{\mathbf{y}} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau}} + \sum_{j(\boldsymbol{\tau})} \nabla \psi_{\mathbf{y}, j} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau} - e_j} \right)^2 \, dx \\ &\quad + \frac{1}{2} \int_D \sum_{j(\boldsymbol{\tau})} |\psi_{\mathbf{y}, j}| (|\Delta t_{\mathbf{y}, \boldsymbol{\tau} - e_j}|^2 + |\Delta t_{\mathbf{y}, \boldsymbol{\tau}}|^2) \Phi_{\boldsymbol{\beta}}^2 \, dx. \end{aligned}$$

For $k \geq 1$, by a twofold application of the Cauchy–Schwarz inequality (applied to the sum) and **(A2)**

$$\begin{aligned}
& \sum_{|\boldsymbol{\tau}|=k} \int_D \frac{\Phi_{\boldsymbol{\beta}}^2}{\bar{a}_{\mathbf{y}}} \left(\nabla \bar{a}_{\mathbf{y}} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau}} + \sum_{j(\boldsymbol{\tau})} \nabla \psi_{\mathbf{y}, j} \cdot \nabla t_{\mathbf{y}, \boldsymbol{\tau} - e_j} \right)^2 dx \\
& \leq 2K \int_D \frac{\Phi_{\boldsymbol{\beta}}}{\bar{a}_{\mathbf{y}}} \left(|\nabla \bar{a}_{\mathbf{y}}| \sum_{|\boldsymbol{\tau}|=k} |\nabla t_{\mathbf{y}, \boldsymbol{\tau}}|^2 + \sum_{|\boldsymbol{\tau}|=k-1} \sum_{j \geq 1} |\nabla \psi_{\mathbf{y}, j}| |\nabla t_{\mathbf{y}, \boldsymbol{\tau}}|^2 \right) dx \\
& \leq \frac{4K^2}{(\bar{a}_{\mathbf{y}, \min})^2} \left(\sum_{|\boldsymbol{\tau}|=k} \|\nabla t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\bar{a}_{\mathbf{y}}}^2 + \sum_{|\boldsymbol{\tau}|=k-1} \|\nabla t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\bar{a}_{\mathbf{y}}}^2 \right).
\end{aligned}$$

Note that also by **(A1)** for every $k \geq 1$,

$$\begin{aligned}
& \sum_{|\boldsymbol{\tau}|=k} \int_D \sum_{j(\boldsymbol{\tau})} |\psi_{\mathbf{y}, j}| (|\Delta t_{\mathbf{y}, \boldsymbol{\tau} - e_j}|^2 + |\Delta t_{\mathbf{y}, \boldsymbol{\tau}}|^2) \Phi_{\boldsymbol{\beta}}^2 dx \\
& \leq \frac{\kappa}{\eta} \left(\sum_{|\boldsymbol{\tau}|=k-1} \|\sqrt{\bar{a}_{\mathbf{y}}} \Delta t_{\mathbf{y}, \boldsymbol{\tau}}\|_{L_{\beta}^2(D)}^2 + \sum_{|\boldsymbol{\tau}|=k} \|\sqrt{\bar{a}_{\mathbf{y}}} \Delta t_{\mathbf{y}, \boldsymbol{\tau}}\|_{L_{\beta}^2(D)}^2 \right).
\end{aligned}$$

We now choose $\varepsilon > 0$ such that $\varepsilon < 1/2(1 - \kappa/\eta)$, which implies $\varepsilon + \kappa/(2\eta) < 1/2$. Then, we sum over $k \geq 1$ to obtain

$$\sum_{k \geq 1} \sum_{|\boldsymbol{\tau}|=k} \|\sqrt{\bar{a}_{\mathbf{y}}} \Delta t_{\mathbf{y}, \boldsymbol{\tau}}\|_{L_{\beta}^2(D)}^2 \leq C \sum_{\boldsymbol{\tau} \in \mathcal{F}} \|\nabla t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\bar{a}_{\mathbf{y}}}^2 + C_{\varepsilon} \sum_{\boldsymbol{\tau} \in \mathcal{F}} \|\sqrt{\bar{a}_{\mathbf{y}}} \Delta t_{\mathbf{y}, \mathbf{0}}\|_{L_{\beta}^2(D)}^2,$$

where $C_{\varepsilon} = 1/2(1 - \kappa/(2\eta) - \varepsilon)^{-1} < 1$ and $C = K^2/(\varepsilon(\bar{a}_{\mathbf{y}, \min})^2)(1 - \kappa/(2\eta) - \varepsilon)^{-1}$. It follows

$$\sum_{\boldsymbol{\tau} \in \mathcal{F}} \|\sqrt{\bar{a}_{\mathbf{y}}} \Delta t_{\mathbf{y}, \boldsymbol{\tau}}\|_{L_{\beta}^2(D)}^2 \leq \frac{C}{1 - C_{\varepsilon}} \sum_{\boldsymbol{\tau} \in \mathcal{F}} \|t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\bar{a}_{\mathbf{y}}}^2 + 2\|\sqrt{\bar{a}_{\mathbf{y}}} \Delta t_{\mathbf{y}, \mathbf{0}}\|_{L_{\beta}^2(D)}^2,$$

which implies the assertion with [10, Lemma 3] and (8). \square

Remark 3. For every truncation dimension $s \in \mathbb{N}$, the estimate in Proposition 2 also holds when $\Delta \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z})|_{\mathbf{z}=\mathbf{0}}$, $\boldsymbol{\tau} \in \mathcal{F}$, are considered and the constant is independent of s . This follows from the observation that $\partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) = \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}_{\{1:s\}}}(\cdot, \mathbf{z})$ if $\tau_j = 0$ for every $j > s$ and $\partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) = 0$ otherwise. Then, the sum of the estimate in Proposition 2 only consists of more terms and is an upper bound.

Proposition 3. *Let the assumption in (A1) be satisfied and let $\boldsymbol{\beta}$ satisfy $\beta_i < 1 - \pi/\omega_i$, $i = 1, \dots, J$. Then, there exists a constant $C > 0$ such that for every $\mathbf{y} \in U$*

$$\sum_{\boldsymbol{\tau} \in \mathcal{F}} \frac{1}{(\boldsymbol{\tau}!)^2} \left\| \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \left(\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^{\mathcal{F}_{\ell}}(\cdot, \mathbf{z}) \right) \Big|_{\mathbf{z}=\mathbf{0}} \right\|_{\mathbf{V}}^2 \leq CM_{\ell}^{-2/d} \|f\|_{L_{\beta}^2(D)}^2.$$

Proof. We argue similarly as in the proof of [10, Lemma 3] and consider the Taylor coefficients for fixed $\mathbf{y} \in U$

$$t_{\mathbf{y}, \boldsymbol{\tau}} := \frac{1}{\boldsymbol{\tau}!} \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) \Big|_{\mathbf{z}=\mathbf{0}} \quad \text{and} \quad t_{\mathbf{y}, \boldsymbol{\tau}}^{\ell} := \frac{1}{\boldsymbol{\tau}!} \partial_{\mathbf{z}}^{\boldsymbol{\tau}} \tilde{u}_{\mathbf{y}}^{\mathcal{F}_{\ell}}(\cdot, \mathbf{z}) \Big|_{\mathbf{z}=\mathbf{0}}, \quad \boldsymbol{\tau} \in \mathcal{F}.$$

We observe that

$$\int_D \bar{a}_{\mathbf{y}} \nabla(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell) \cdot \nabla v \, dx = - \sum_{j(\boldsymbol{\tau})} \psi_{\mathbf{y}, j} \nabla(t_{\mathbf{y}, \boldsymbol{\tau} - e_j} - t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^\ell) \cdot \nabla v \, dx, \quad \forall v \in V_\ell.$$

For every $\mathbf{y} \in U$ and for every $\ell \in \mathbb{N}_0$, let $\mathcal{P}_{\mathbf{y}, \ell} : V \rightarrow V_\ell$ denote the dilated Galerkin projection, i.e., for every $w \in V$, $\mathcal{P}_{\mathbf{y}, \ell} w$ is defined by

$$\int_D \bar{a}_{\mathbf{y}} \nabla(w - \mathcal{P}_{\mathbf{y}, \ell} w) \cdot \nabla v \, dx = 0, \quad \forall v \in V_\ell. \quad (19)$$

By the definition of $\mathcal{P}_{\mathbf{y}, \ell}$ in (19) and by testing with $v = \mathcal{P}_{\mathbf{y}, \ell}(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell) \in V_\ell$,

$$\begin{aligned} & \sum_{|\boldsymbol{\tau}|=k} \int_D \bar{a}_{\mathbf{y}} |\nabla \mathcal{P}_{\mathbf{y}, \ell}(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell)|^2 \, dx \\ & \leq \int_D \sum_{|\boldsymbol{\tau}|=k} \sum_{j(\boldsymbol{\tau})} |\psi_{\mathbf{y}, j}| \frac{1}{2} (|\nabla(t_{\mathbf{y}, \boldsymbol{\tau} - e_j} - t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^\ell)|^2 + |\nabla \mathcal{P}_{\mathbf{y}, \ell}(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell)|^2) \, dx \\ & \leq \frac{1}{2} \int_D \sum_{|\boldsymbol{\tau}|=k-1} \sum_{j \geq 1} |\psi_{\mathbf{y}, j}| |\nabla(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell)|^2 \, dx \\ & \quad + \frac{1}{2} \int_D \sum_{|\boldsymbol{\tau}|=k-1} \sum_{j \geq 1} |\psi_{\mathbf{y}, j}| |\nabla \mathcal{P}_{\mathbf{y}, \ell}(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell)|^2 \, dx, \end{aligned}$$

which implies with **(A1)**

$$\begin{aligned} \sum_{|\boldsymbol{\tau}|=k} \|\mathcal{P}_{\mathbf{y}, \ell}(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell)\|_{\bar{a}_{\mathbf{y}}}^2 & \leq \frac{1}{2 - \kappa/\eta} \int_D \sum_{|\boldsymbol{\tau}|=k} \sum_{j(\boldsymbol{\tau})} |\psi_{\mathbf{y}, j}| |\nabla(t_{\mathbf{y}, \boldsymbol{\tau} - e_j} - t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^\ell)|^2 \, dx \\ & \leq \frac{1}{2 - \kappa/\eta} \frac{\kappa}{\eta} \sum_{|\boldsymbol{\tau}|=k-1} \|t_{\mathbf{y}, \boldsymbol{\tau} - e_j} - t_{\mathbf{y}, \boldsymbol{\tau} - e_j}^\ell\|_{\bar{a}_{\mathbf{y}}}^2. \end{aligned} \quad (20)$$

Note that by the triangle inequality

$$\|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell\|_{\bar{a}_{\mathbf{y}}} \leq \|\mathcal{P}_{\mathbf{y}, \ell}(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell)\|_{\bar{a}_{\mathbf{y}}} + \|(\mathcal{I} - \mathcal{P}_{\mathbf{y}, \ell})t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\bar{a}_{\mathbf{y}}},$$

where $\mathcal{I} : V \rightarrow V$ denote the identity. With the Young inequality we obtain for any $\varepsilon > 0$ and the previous two inequalities

$$\begin{aligned} & \sum_{|\boldsymbol{\tau}|=k} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2 \\ & \leq \frac{(1 + \varepsilon)\kappa}{2\eta - \kappa} \sum_{|\boldsymbol{\tau}|=k-1} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2 + \left(1 + \frac{1}{\varepsilon}\right) \sum_{|\boldsymbol{\tau}|=k} \|(\mathcal{I} - \mathcal{P}_{\mathbf{y}, \ell})t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\bar{a}_{\mathbf{y}}}^2. \end{aligned}$$

Since $\kappa < \eta < 1$, $2\eta - \kappa > 1$ and so we choose $\varepsilon > 0$ such that $(1 + \varepsilon)\kappa < 1$ and conclude by subtracting the first sum in the previous inequality that

$$\sum_{k \geq 1} \sum_{|\boldsymbol{\tau}|=k} \|t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell\|_{\tilde{a}_{\mathbf{y}}}^2 \leq \|t_{\mathbf{y}, \mathbf{0}} - t_{\mathbf{y}, \mathbf{0}}^\ell\|_{\tilde{a}_{\mathbf{y}}}^2 + \frac{2\eta - \kappa}{\varepsilon \kappa} \sum_{k \geq 1} \sum_{|\boldsymbol{\tau}|=k} \|(\mathcal{I} - \mathcal{P}_{\mathbf{y}, \ell})t_{\mathbf{y}, \boldsymbol{\tau}}\|_{\tilde{a}_{\mathbf{y}}}^2,$$

which implies the assertion with (7), (6), and Proposition 2. \square

Remark 4. The estimate in Proposition 3 holds if $f \in (V^*, L_{\boldsymbol{\beta}}^2(D))_{t, \infty}$ with the error being controlled by $M_\ell^{-2t/d}$, $t \in [0, 1]$. This can be seen by interpolation applied in the last step of the proof of Proposition 3, where (7), (6), and Proposition 2 were used (see also Remark 1).

Lemma 1. For every $c \in (1, \infty)$ and every $\boldsymbol{\tau} \in \mathcal{F}$,

$$|\boldsymbol{\tau}| \leq \frac{1}{\log(c)e} c^{|\boldsymbol{\tau}|} = \frac{1}{\log(c)e} \prod_{j \geq 1} c^{\tau_j}.$$

Proof. Let $\alpha > 0$ be arbitrary. By elementary calculus, we observe that the function $x \mapsto \log(x)/x^\alpha$ has a maximum at $x_0 = e^{1/\alpha}$. Since $\lim_{x \rightarrow \infty} \log(x)/x^\alpha = 0$, this maximum is global on $[1, \infty)$. Hence, $\log(x) \leq x^\alpha/(\alpha e)$ for every $x \in [1, \infty)$.

Then, $\sum_{j \geq 1} \tau_j = \log(\prod_{j \geq 1} e^{\tau_j}) \leq 1/(\alpha e) \prod_{j \geq 1} e^{\alpha \tau_j} = 1/(\alpha e) c^{|\boldsymbol{\tau}|}$, where α is chosen to be $\alpha = \log(c) > 0$. \square

For any $G \in V^*$, we introduce $u_G(\cdot, \mathbf{y})$ and $u_G^{\mathcal{J}_\ell}(\cdot, \mathbf{y})$, $\ell \in \mathbb{N}_0$, as the parametric solution to the dual problem of (4) and the parametric FE solution to the dual problem of (9), respectively, with right hand side G . Consideration of the dilated coefficient resulting from (13) gives $\tilde{u}_{G, \mathbf{y}}(\cdot, \mathbf{z})$ and $\tilde{u}_{G, \mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})$, $\ell \in \mathbb{N}_0$. By an Aubin–Nitsche argument, for every $\mathbf{y} \in U$ and every $\mathbf{z} \in \tilde{U}$,

$$G(\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})) = \int_D \tilde{a}_{\mathbf{y}}(\cdot, \mathbf{z}) \nabla(\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})) \cdot \nabla(\tilde{u}_{G, \mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{G, \mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})) dx. \quad (21)$$

Theorem 2. Let the assumption in (A1) be satisfied. Then, for every $c > 1$ there exists a constant $C > 0$ such that for every $G(\cdot) \in L_{\boldsymbol{\beta}}^2(D)$

$$\begin{aligned} & \sum_{\boldsymbol{\tau} \in \mathcal{F}} \frac{1}{c^{|\boldsymbol{\tau}|} (\boldsymbol{\tau}!)^2} \left| \partial_{\mathbf{z}}^{\boldsymbol{\tau}} G(\tilde{u}_{\mathbf{y}}(\cdot, \mathbf{z}) - \tilde{u}_{\mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})) \Big|_{\mathbf{z}=\mathbf{0}} \right|^2 \\ & \leq C M_\ell^{-4/d} \|f\|_{L_{\boldsymbol{\beta}}^2(D)}^2 \|G(\cdot)\|_{L_{\boldsymbol{\beta}}^2(D)}. \end{aligned}$$

Proof. The Taylor coefficients of $\tilde{u}_{G, \mathbf{y}}(\cdot, \mathbf{z})$ and $\tilde{u}_{G, \mathbf{y}}^{\mathcal{J}_\ell}(\cdot, \mathbf{z})$ will be denoted by $\hat{t}_{\mathbf{y}, \boldsymbol{\tau}}$ and $\hat{t}_{\mathbf{y}, \boldsymbol{\tau}}^\ell$, $\boldsymbol{\tau} \in \mathcal{F}$, respectively (see also (18)). By differentiating (21), for every $\mathbf{0} \neq \boldsymbol{\tau} \in \mathcal{F}$,

$$G(t_{\mathbf{y}, \boldsymbol{\tau}} - t_{\mathbf{y}, \boldsymbol{\tau}}^\ell) = \sum_{\mathbf{v} \leq \boldsymbol{\tau}} \int_D \left[\sum_{j(\mathbf{v})} \psi_{\mathbf{y}, j} \nabla(t_{\mathbf{y}, \mathbf{v} - e_j} - t_{\mathbf{y}, \mathbf{v} - e_j}^\ell) \right] \cdot \nabla(\hat{t}_{\mathbf{y}, \boldsymbol{\tau} - \mathbf{v}} - \hat{t}_{\mathbf{y}, \boldsymbol{\tau} - \mathbf{v}}^\ell) dx.$$

Squaring the previous equality and applying the Cauchy–Schwarz inequality and Lemma 1 to obtain with $C = 1/(\log(c)e)$

$$|G(t_{\mathbf{y},\boldsymbol{\tau}} - t_{\mathbf{y},\boldsymbol{\tau}}^\ell)|^2 \leq C c^\tau \sum_{\mathbf{v} \leq \boldsymbol{\tau}} \left\| \sqrt{1/\bar{a}_{\mathbf{y}}}[\dots] \right\|_{L^2(D)}^2 \|\widehat{t}_{\mathbf{y},\boldsymbol{\tau}-\mathbf{v}} - \widehat{t}_{\mathbf{y},\boldsymbol{\tau}-\mathbf{v}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2,$$

where we used that $\sum_{\mathbf{v} \leq \boldsymbol{\tau}} = |\boldsymbol{\tau}|$. By changing the order of summation

$$\begin{aligned} \sum_{\boldsymbol{\tau} \in \mathcal{F}} \frac{1}{c^\tau} |G(t_{\mathbf{y},\boldsymbol{\tau}} - t_{\mathbf{y},\boldsymbol{\tau}}^\ell)|^2 &\leq C \sum_{\mathbf{v} \in \mathcal{F}} \left\| \sqrt{1/\bar{a}_{\mathbf{y}}}[\dots] \right\|_{L^2(D)}^2 \sum_{\boldsymbol{\tau} \in \mathcal{F}, \boldsymbol{\tau} \geq \mathbf{v}} \|\widehat{t}_{\mathbf{y},\boldsymbol{\tau}-\mathbf{v}} - \widehat{t}_{\mathbf{y},\boldsymbol{\tau}-\mathbf{v}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2 \\ &= C \sum_{\mathbf{v} \in \mathcal{F}} \left\| \sqrt{1/\bar{a}_{\mathbf{y}}}[\dots] \right\|_{L^2(D)}^2 \sum_{\boldsymbol{\tau} \in \mathcal{F}} \|\widehat{t}_{\mathbf{y},\boldsymbol{\tau}} - \widehat{t}_{\mathbf{y},\boldsymbol{\tau}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2. \end{aligned} \tag{22}$$

By the Cauchy–Schwarz inequality we obtain with **(A1)**

$$\left\| \sqrt{1/\bar{a}_{\mathbf{y}}}[\dots] \right\|_{L^2(D)}^2 \leq \frac{\kappa}{\eta} \int_D \sum_{j(\mathbf{v})} |\psi_{\mathbf{y},j}| |\nabla(t_{\mathbf{y},\mathbf{v}-e_j} - t_{\mathbf{y},\mathbf{v}-e_j}^\ell)|^2 dx.$$

By another application of the Cauchy–Schwarz inequality and **(A1)**

$$\sum_{k \geq 1} \sum_{|\mathbf{v}|=k} \left\| \sqrt{1/\bar{a}_{\mathbf{y}}}[\dots] \right\|_{L^2(D)}^2 \leq \left(\frac{\kappa}{\eta} \right)^2 \sum_{k \geq 1} \sum_{|\mathbf{v}|=k-1} \|t_{\mathbf{y},\mathbf{v}} - t_{\mathbf{y},\mathbf{v}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2,$$

which implies with (22)

$$\sum_{\boldsymbol{\tau} \in \mathcal{F}} \frac{1}{c^\tau} |G(t_{\mathbf{y},\boldsymbol{\tau}} - t_{\mathbf{y},\boldsymbol{\tau}}^\ell)|^2 \leq C \left(\sum_{\boldsymbol{\tau} \in \mathcal{F}} \|t_{\mathbf{y},\boldsymbol{\tau}} - t_{\mathbf{y},\boldsymbol{\tau}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2 \right) \left(\sum_{\boldsymbol{\tau} \in \mathcal{F}} \|\widehat{t}_{\mathbf{y},\boldsymbol{\tau}} - \widehat{t}_{\mathbf{y},\boldsymbol{\tau}}^\ell\|_{\bar{a}_{\mathbf{y}}}^2 \right).$$

The assertion now follows with Proposition 3. \square

Remark 5. The estimate in Theorem 2 also holds if $f \in (V^*, L^2_{\boldsymbol{\beta}})_{t,\infty}$ and $G(\cdot) \in (V^*, L^2_{\boldsymbol{\beta}})_{t',\infty}$, $t, t' \in [0, 1]$, with error control $M_\ell^{-2(t+t')/d}$, which follows by Remark 4.

Remark 6. For every truncation dimension $s \in \mathbb{N}$, the estimates in Proposition 3 and Theorem 2 also hold when the differences $\partial_{\mathbf{z}}^{\boldsymbol{\tau}}(\widehat{u}_{\mathbf{y}}^s(\cdot, \mathbf{z}) - \widehat{u}_{\mathbf{y}}^{s, \mathcal{F}_\ell}(\cdot, \mathbf{z}))|_{\mathbf{z}=\mathbf{0}}$, $\boldsymbol{\tau} \in \mathcal{F}$, are considered and the constant is independent of s . This follows by the same argument which is used to verify Remark 3.

5 Convergence of multilevel QMC

The parametric regularity estimates from Section 4 will result in explicit error estimates of multilevel QMC. Let the sequence $(\mathbf{b}_j)_{j \geq 1}$ be a generic input for the QMC

weights. For interlaced polynomial lattice rules with interlacing factor $\alpha \geq 2$ we will consider the product weights $\boldsymbol{\gamma}^{\text{IP}} = (\gamma_{\mathbf{u}}^{\text{IP}})_{\mathbf{u} \subset \mathbb{N}}$ given by $\gamma_{\emptyset}^{\text{IP}} := 1$ and

$$\gamma_{\mathbf{u}}^{\text{IP}} := \prod_{j \in \mathbf{u}} \left(\sum_{v=1}^{\alpha} \left(\frac{2b_j}{1-\eta} \right)^v \sqrt{2^{\delta(v,\alpha)} v!} \right), \quad \mathbf{u} \subset \mathbb{N}, |\mathbf{u}| < \infty, \quad (23)$$

and for randomly shifted lattice rules the product weights $\boldsymbol{\gamma}^{\text{RS}} = (\gamma_{\mathbf{u}}^{\text{RS}})_{\mathbf{u} \subset \mathbb{N}}$ given by $\gamma_{\emptyset}^{\text{RS}} := 1$ and

$$\gamma_{\mathbf{u}}^{\text{RS}} := \prod_{j \in \mathbf{u}} \left(\frac{2b_j}{1-\eta} \right)^2, \quad \mathbf{u} \subset \mathbb{N}, |\mathbf{u}| < \infty. \quad (24)$$

We will apply a QMC rule on levels $\ell = 1, \dots, L$ and in general a different version on the level $\ell = 0$. The parametric regularity estimates that were derived in Section 4 are based on a dilated coordinate, cp. (13) and (15), with respect to sequences $(b_j^{1-\theta})_{j \geq 1}$ for the truncation error and $(\bar{b}_j)_{j \geq 1}$ for the FE error. These sequences will be the input for the product weights. Their summability in terms of membership in $\ell^{\bar{p}}(\mathbb{N})$, $\bar{p} \in (0, 2]$, will result in explicit bounds of the coupled errors between the levels. On the levels $\ell = 1, \dots, L$, we use $(c(b_j^{1-\theta} \wedge \bar{b}_j))_{j \geq 1} := (\max\{cb_j^{1-\theta}, c\bar{b}_j\})_{j \geq 1}$ as input for the product weights in (23) and (24) for a constant $c > 1$, i.e. here $(b_j)_{j \geq 1} = (c(b_j^{1-\theta} \wedge \bar{b}_j))_{j \geq 1}$. On the level $\ell = 0$ we use $(b_j)_{j \geq 1}$ as an input for (23) and (24), which has potentially stronger summability properties.

Theorem 3. *Let the assumption in (A1) be satisfied by $(b_j)_{j \geq 1}$ and by $(\bar{b}_j)_{j \geq 1}$. Let the assumption in (A2) be satisfied by $(\bar{b}_j)_{j \geq 1}$. Let $(b_j)_{j \geq 1} \in \ell^p(\mathbb{N})$ for some $p \in (0, 2]$ and assume that $(b_j^{1-\theta} \wedge \bar{b}_j)_{j \geq 1} \in \ell^{\bar{p}}(\mathbb{N})$ for some $\bar{p} \in [p, 2]$ and any $\theta \in [0, 1]$ admitting this summability. For $p \in (0, 1]$ and $\bar{p} \in [p, 1]$, Q_L^{IP} , $L \in \mathbb{N}$, satisfies with product weights (23) and order $\alpha = \lfloor 1/p + 1 \rfloor$ on level $\ell = 0$, and of order $\bar{\alpha} = \lfloor 1/\bar{p} + 1 \rfloor$ on levels $\ell = 1, \dots, L$, the error estimate*

$$\begin{aligned} |\mathbb{E}(G(u)) - Q_L^{\text{IP}}(G(u^L))| &\leq C \left(\sup_{j > s_L} \{b_j^2\} + M_L^{-2/d} + N_0^{-1/p} \right. \\ &\quad \left. + \sum_{\ell=1}^L N_\ell^{-1/\bar{p}} \left(\xi_{\ell, \ell-1} \sup_{j > s_{\ell-1}} \{b_j^\theta\} + M_{\ell-1}^{-2/d} \right) \right), \end{aligned}$$

where $\xi_{\ell, \ell-1} := 0$ if $s_\ell = s_{\ell-1}$ and $\xi_{\ell, \ell-1} := 1$ otherwise. For $p \in (1, 2]$ and $\bar{p} \in [p, 2]$, Q_L^{RS} , $L \in \mathbb{N}$, satisfies with product weights (24) the error estimate

$$\begin{aligned} &\sqrt{\mathbb{E}^\Delta (|\mathbb{E}(G(u)) - Q_L(G(u^L))|^2)} \\ &\leq C \left(\sup_{j > s_L} \{b_j^4\} + M_L^{-4/d} + (\varphi(N_0))^{-2/p} \right. \\ &\quad \left. + \sum_{\ell=1}^L (\varphi(N_\ell))^{-2/\bar{p}} \left(\xi_{\ell, \ell-1} \sup_{j > s_{\ell-1}} \{b_j^{2\theta}\} + M_{\ell-1}^{-4/d} \right) \right)^{1/2}. \end{aligned}$$

The constant C is in particular independent of L , $(N_\ell)_{\ell \geq 0}$, $(M_\ell)_{\ell \geq 0}$, and $(s_\ell)_{\ell \geq 0}$.

Proof. By the error estimates in (12) and (11), we have to estimate the difference $G(u^\ell - u^{\ell-1}) = G(u^{s_\ell, \mathcal{T}_\ell} - u^{s_{\ell-1}, \mathcal{T}_{\ell-1}})$ in the $\mathcal{W}_{s_\ell, \alpha, \gamma, \infty, \infty}$ -norm and in the $\mathcal{W}_{s_\ell, \gamma}$ -norm, $\ell = 1, \dots, L$. We decompose by the triangle inequality

$$\begin{aligned} & \|G(u^{s_\ell, \mathcal{T}_\ell} - u^{s_{\ell-1}, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}} \\ & \leq \|G(u^{s_\ell, \mathcal{T}_\ell} - u^{s_\ell, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}} + \|G(u^{s_\ell, \mathcal{T}_{\ell-1}} - u^{s_{\ell-1}, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}}, \end{aligned}$$

and

$$\|G(u^{s_\ell, \mathcal{T}_\ell} - u^{s_\ell, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}} \leq \|G(u^{s_\ell} - u^{s_\ell, \mathcal{T}_\ell})\|_{\mathcal{W}_{s_\ell, \gamma}} + \|G(u^{s_\ell} - u^{s_\ell, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}}.$$

The contributions from the dimension truncation and the FE error have been separated in the $\mathcal{W}_{s_\ell, \gamma}$ -norm. For the dimension truncation error, we obtain by the Jensen inequality, the relation of higher order partial derivative in terms of the dilated coordinate in (16), Theorem 1, and Remark 2

$$\begin{aligned} & \|G(u^{s_\ell, \mathcal{T}_{\ell-1}} - u^{s_{\ell-1}, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}}^2 \\ & \leq \|G(\cdot)\|_{V^*} \int_{[-\frac{1}{2}, \frac{1}{2}]^s} \sum_{u \subset \{1:s\}} (\gamma_u^{\text{RS}})^{-1} \|\partial_{\mathbf{y}}^u (u^{s_\ell, \mathcal{T}_{\ell-1}}(\cdot, \mathbf{y}) - u^{s_{\ell-1}, \mathcal{T}_{\ell-1}}(\cdot, \mathbf{y}))\|_{V}^2 d\mathbf{y} \\ & \leq C \|G(\cdot)\|_{V^*} \|f\|_{V^*} \sup_{u \subset \{1:s\}} (\gamma_u^{\text{RS}})^{-1} \prod_{j \in u} \left(\frac{2b_j^{1-\theta}}{1-\eta} \right)^2 \sup_{j > s_\ell} \{b_j^{2\theta}\}. \end{aligned}$$

Due to the choice of the weights, there exists a constant $C > 0$ independent of the sequences $(s_\ell)_{\ell \geq 0}$ and $\{\mathcal{T}_\ell\}_{\ell \geq 0}$ such that

$$\|G(u^{s_\ell, \mathcal{T}_{\ell-1}} - u^{s_{\ell-1}, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}} \leq C \|G(\cdot)\|_{V^*} \|f\|_{V^*} \sup_{j > s_\ell} \{b_j^\theta\}.$$

Note that if $s_\ell = s_{\ell-1}$ this difference is zero. Similarly, we obtain with Theorem 2 and Remark 4 that there exists a constant $C > 0$ which is independent of $(s_\ell)_{\ell \geq 0}$ and $(M_\ell)_{\ell \geq 0}$ such that for every $\ell \in \mathbb{N}$

$$\|G(u^{s_\ell} - u^{s_\ell, \mathcal{T}_{\ell-1}})\|_{\mathcal{W}_{s_\ell, \gamma}} \leq C \|G(\cdot)\|_{L^2_{\beta}(D)} \|f\|_{L^2_{\beta}(D)} M_{\ell-1}^{-2/d}.$$

Note that here the constant $c > 1$ in the weight sequence is necessary to compensate c in the estimate of Theorem 2. The corresponding estimate on the level $\ell = 0$ of $\|G(u^{s_0, \mathcal{T}_0})\|_{\mathcal{W}_{s_0, \gamma}}$ is due to [10, Corollary 5], which is also applicable in the case of a dimensionally truncated FE solution, cp. Remarks 2 and 4. The estimate for the randomly shifted lattice rules follows then with (10) and (11) with $\lambda = p/2$.

The proof for interlaced polynomial lattice rules follows along the same lines, where the estimate $\|F\|_{\mathcal{W}_{s_\ell, \alpha, \gamma, \infty, \infty}} \leq \|F\|_{\mathcal{W}_{s_\ell, \alpha, \gamma, 2, 2}}$, $F \in \mathcal{W}_{s_\ell, \alpha, \gamma, 2, 2}$, is used and [10, Corollary 7] is used for the level $\ell = 0$ (see also the proof of [10, Proposition 6]). \square

Remark 7. The estimate in Theorem 3 also holds if $f \in (V^*, L_{\beta}^2)_{t, \infty}$ and $G(\cdot) \in (V^*, L_{\beta}^2)_{t', \infty}$, $t, t' \in [0, 1]$, with an error contribution of $M_{\ell}^{-(t+t')/d}$ and $M_{\ell}^{-2(t+t')/d}$ in the estimates for Q^{IP} and Q^{RS} , respectively. This follows by Remark 5.

Remark 8. The factor $2/(1-\eta)$ in the weights in (23) and (24) as well as the constant $c > 1$ in the sequence $(c(b_j^{1-\theta} \wedge \bar{b}_j))_{j \geq 1}$ can be omitted. Then, the error estimates in Theorem 3 hold under the same assumptions with QMC convergence rates $1/p - \varepsilon$ and $1/\bar{p} - \varepsilon$ in the multilevel error estimates for every sufficiently small $\varepsilon > 0$. This can be seen by the same argument that we used to show [10, Corollary 11] (see also [10, Corollary 13]).

6 Error vs. work analysis

The error estimates in Theorem 3 are the key ingredient to calibrate and choose the parameters $(s_{\ell})_{\ell \geq 0}$, $(M_{\ell})_{\ell \geq 0}$, $\theta \in [0, 1)$, and $(N_{\ell})_{\ell \geq 0}$ of either considered type of the multilevel QMC algorithm. We seek to derive choices that optimize the work for a given error threshold. The analysis will be demonstrated for a class of multiresolution analyses (MRA for short), which will serve as the function system $(\psi_j)_{j \geq 1}$. We will use notation that is standard for wavelets and MRA. Assume that $(\psi_{\lambda})_{\lambda \in \nabla}$ is a MRA that is obtained by scaling and translation from a finite number of mother wavelets, i.e.,

$$\psi_{\lambda}(x) = \psi(2^{|\lambda|}x - k), \quad k \in \nabla_{|\lambda|}, x \in D.$$

The index set $\nabla_{|\lambda|}$ has cardinality $|\nabla_{|\lambda|}| = \mathcal{O}(2^{|\lambda|d})$ and $|\text{supp}(\psi_{\lambda})| = \mathcal{O}(2^{-|\lambda|d})$. Let $j : \nabla \rightarrow \mathbb{N}$ be a suitable bijective enumeration. We also assume that on every level $|\lambda|$ there is a finite overlap, i.e., there exists $K > 0$ such that for every $i \in \mathbb{N}_0$ and every $x \in D$

$$|\{\lambda \in \nabla : |\lambda| = i, \psi_{\lambda}(x) \neq 0\}| \leq K.$$

The work needed to assemble the stiffness matrix for a generic $\mathbf{y} \in [-1/2, 1/2]^s$ is therefore $\mathcal{O}(M_{\ell} |j^{-1}(s_{\ell})|) = \mathcal{O}(M_{\ell} \log(s_{\ell}))$. Assuming at hand a linear complexity solver, the overall work for either multilevel QMC algorithm with $L \in \mathbb{N}_0$ levels satisfies

$$\text{work} = \mathcal{O} \left(\sum_{\ell=0}^L N_{\ell} M_{\ell} \log(s_{\ell}) \right).$$

Note that error vs. work estimate for general function systems have been derived in [20, 6].

The parameter θ in the coupled estimates of Theorem 3 allows to discuss two possible strategies in the choices of the truncation levels $(s_{\ell})_{\ell \geq 0}$. We recall from [10, Section 8] that if $\|\psi_{j(\lambda)}\|_{L^{\infty}(D)} \leq \sigma 2^{\hat{\alpha}|\lambda|}$ the sequence

$$b_{j(\lambda)} = \left(1 + \frac{\bar{a}_{\min}(1-\kappa)(1-2^{\widehat{\beta}-\widehat{\alpha}})}{\sigma 2K} 2^{\widehat{\beta}|\lambda|} \right)^{-1}, \quad j \in \mathbb{N}, \quad (25)$$

satisfies **(A1)** for $\widehat{\alpha} > \widehat{\beta} > 1$ and $b_j \sim j^{-\widehat{\beta}/d}$, $j \geq 1$ holds. The sequence

$$\bar{b}_j = b_j^{(\widehat{\beta}-1)/\widehat{\beta}}, \quad j \in \mathbb{N},$$

satisfies **(A2)** and **(A1)** and $\bar{b}_j \sim j^{-(\widehat{\beta}-1)/d}$, $j \geq 1$ holds. Note that $\|\nabla \psi_{j(\lambda)}\|_{L^\infty(D)} \leq \sigma 2^{-(\widehat{\alpha}-1)|\lambda|}$. The truncation levels $(s_\ell)_{\ell \geq 0}$ are chosen so as to cover entire levels of the MRA expansion of the uncertain PDE input, so that we choose $s_\ell \in \{\sum_{i=0}^{\ell} |\nabla_i| : I \in \mathbb{N}_0\}$, $\ell \geq 0$. We also assume that

$$M_\ell \sim 2^{d\ell}, \quad \ell \geq 0. \quad (\text{A3})$$

In this section we assume for simplicity that only one version of the QMC rule is applied with convergence rate \bar{p} . We remark that in some cases the application of two different weight sequences with different sparsity may be beneficial. Also we assume that

$$f \in (V^*, L_{\beta}^2(D))_{t,\infty} \quad \text{and} \quad G(\cdot) \in (V^*, L_{\beta}^2(D))_{t',\infty}, \quad t, t' \in [0, 1], \quad (\text{A4})$$

which yields a FE convergence rate of $\tau := t + t' \in [0, 2]$, cp. Remark 7.

Strategy 1: We equilibrate the decay of the sequences $(b_j^{1-\theta})_{j \geq 1}$ and $(\bar{b}_j)_{j \geq 1}$, which determines the estimate of the QMC error in Theorem 3. The parameter $\theta \in [0, 1)$ is chosen to be $\theta = 1/\widehat{\beta}$, which implies $b_j^{1-\theta} = \bar{b}_j$, $j \in \mathbb{N}$, and $(\bar{b}_j)_{j \geq 0} \in \ell^{\bar{p}}(\mathbb{N})$ for every $\bar{p} > d/(\widehat{\beta} - 1)$. We equilibrate the error contributions on the highest level L . Since $s_L \sim 2^{dL} \sim M_L$, we choose

$$s_L \sim 2^{d \lceil L\tau/(2\widehat{\beta}) \rceil}.$$

On the different levels of the coupled error terms, we either increase the truncation levels or leave it constant, which is reflected in the choice

$$s_\ell \sim \min \left\{ 2^{d \lceil \ell\tau/(d\theta\widehat{\beta}) \rceil}, s_L \right\}, \quad \ell = 0, \dots, L-1.$$

Strategy 2: For certain function systems $(\psi_\lambda)_{\lambda \in \nabla}$ and meshes $\{\mathcal{T}_\ell\}_{\ell \geq 0}$ it may be interesting (also for implementation purposes) to couple their discretizations, i.e., we choose

$$s_\ell \sim M_\ell, \quad \ell = 0, \dots, L.$$

To equilibrate the truncation and FE error on the levels we choose $\theta = \tau/\widehat{\beta}$, which imposes the constraint $\widehat{\beta} > \tau$ and implies that $b_j^{1-\theta} \sim j^{-(\widehat{\beta}-\tau)/d}$. Hence, $(b_j^{1-\theta} \wedge$

$\bar{b}_j)_{j \geq 1} \in \ell^{\bar{p}}(\mathbb{N})$ for every $\bar{p} > d/(\min\{\hat{\beta} - \tau, \hat{\beta} - 1\})$.

We will discuss interlaced polynomial lattice rules first and follow [6, Section 3.3]. In either of our parameter choices, the error estimate

$$\text{error} = \mathcal{O} \left(M_L^{-\tau/d} + \sum_{\ell=0}^L N_\ell^{-1/\bar{p}} M_\ell^{-\tau/d} \right)$$

holds, where we used that $M_\ell = \mathcal{O}(2^{d\ell})$. The QMC sample numbers $(N_\ell)_{\ell=0, \dots, L}$ are chosen to optimize the error versus the required work. Optimizing error (bound) vs. cost as in [20, 6], we search the stationary point of the function

$$g(\xi) = M_L^{-\tau/d} + \sum_{\ell=0}^L N_\ell^{-1/\bar{p}} M_\ell^{-\tau/d} + \xi \sum_{\ell=0}^L N_\ell M_\ell \log(s_\ell)$$

with respect to N_ℓ , i.e., choose N_ℓ such that $\partial g(\xi)/\partial N_\ell = 0$. We thus obtain

$$N_\ell = \left\lceil N_0 \left(M_\ell^{-1-\tau/d} \log(s_\ell)^{-1} \right)^{\bar{p}/(1+\bar{p})} \right\rceil, \quad \ell = 1, \dots, L. \quad (26)$$

and for $E_\ell := (M_\ell^{1-\bar{p}\tau/d} \log(s_\ell))^{1/(\bar{p}+1)}$,

$$\text{error} = \mathcal{O} \left(M_L^{-\tau/d} + N_0^{-1/\bar{p}} \sum_{\ell=0}^L E_\ell \right) \quad \text{and} \quad \text{work} = \mathcal{O} \left(N_0 \sum_{\ell=0}^L E_\ell \right).$$

Since for every $0 \neq r_1 \in \mathbb{R}$ and $r_2 > 0$,

$$\sum_{\ell=0}^L 2^{r_1 \ell} \ell^{r_2} \leq \frac{2^{r_1(L+1)} - 1}{2^{r_1} - 1} L^{r_2},$$

$\log(s_\ell) = \mathcal{O}(\ell)$, which holds in the considered cases, implies that

$$\sum_{\ell=0}^L E_\ell = \begin{cases} \mathcal{O}(1) & \text{if } d < \bar{p}\tau, \\ \mathcal{O}(L^{(\bar{p}+2)/(\bar{p}+1)}) & \text{if } d = \bar{p}\tau, \\ \mathcal{O}(2^{(d-\bar{p}\tau)L/(\bar{p}+1)} L^{1/(\bar{p}+1)}) & \text{if } d > \bar{p}\tau. \end{cases}$$

We choose N_0 to equilibrate the error, i.e.,

$$N_0^{-1/\bar{p}} \sum_{\ell=0}^L E_\ell = \mathcal{O} \left(M_L^{-\tau/d} \right),$$

which yields

$$N_0 := \begin{cases} \lceil 2^{\tau \bar{p} L} \rceil & \text{if } d < \bar{p} \tau, \\ \lceil 2^{\tau \bar{p} L} L^{\bar{p}(\bar{p}+2)/(\bar{p}+1)} \rceil & \text{if } d = \bar{p} \tau, \\ \lceil 2^{\bar{p}(d+\tau)/(\bar{p}+1)} L^{\bar{p}/(\bar{p}+1)} \rceil & \text{if } d > \bar{p} \tau. \end{cases} \quad (27)$$

This implies that an error $= \mathcal{O}(M_L^{-\tau/d})$ requires

$$\text{work} = \begin{cases} \mathcal{O}(2^{\bar{p} \tau L}) & \text{if } d < \bar{p} \tau, \\ \mathcal{O}(2^{\tau \bar{p} L} L^{\bar{p}+2}) & \text{if } d = \bar{p} \tau, \\ \mathcal{O}(2^{dL}) & \text{if } d > \bar{p} \tau. \end{cases}$$

In the other case of randomly shifted lattice rules sample numbers $(N_\ell)_{\ell=0,\dots,L}$ are derived in [20, Section 3.7]. There, also the work functional from a MRA is considered, cp. [20, Equations (74) and (77)] with $\lambda = \bar{p}/2$ and $K_\ell = M_\ell \log(M_\ell) \sim 2^{d\ell}$. Specifically, for randomly shifted lattice rules we choose

$$N_\ell = \left\lceil N_0 \left(M_\ell^{-1-2\tau/d} \log(s_\ell)^{-1} \right)^{\bar{p}/(2+\bar{p})} \right\rceil, \quad \ell = 1, \dots, L, \quad (28)$$

and

$$N_0 := \begin{cases} \lceil 2^{\tau \bar{p} L} \rceil & \text{if } d < \bar{p} \tau, \\ \lceil 2^{\tau \bar{p} L} L^{\bar{p}(\bar{p}+4)/(2\bar{p}+4)} \rceil & \text{if } d = \bar{p} \tau, \\ \lceil 2^{\bar{p}(d+2\tau)/(\bar{p}+2)} L^{\bar{p}/(\bar{p}+1)} \rceil & \text{if } d > \bar{p} \tau. \end{cases} \quad (29)$$

The work estimates for these choices in the case of randomly shifted lattice rules are stated on [20, p. 443]. We collect the foregoing estimates in the following theorem.

Theorem 4. *Let the assumption in (A3) be satisfied and let for $L \in \mathbb{N}$ and $Q_L^{\text{IP}}(\cdot)$, the sample numbers $(N_\ell)_{\ell=0,\dots,L}$ be given by (26) and (27) and for Q_L^{RS} , be given by (28) and (29). Let the right hand side f and $G(\cdot)$ satisfy (A4). For $\bar{p} \in (d/(\hat{\beta} - 1), 1]$, assuming $d < \hat{\beta} - 1$ and error threshold $\varepsilon > 0$,*

$$|\mathbb{E}(G(u)) - Q_L^{\text{IP}}(G(u^L))| = \mathcal{O}(\varepsilon)$$

and

$$\text{work} = \begin{cases} \mathcal{O}(\varepsilon^{-\bar{p}}) & \text{if } d < \bar{p} \tau, \\ \mathcal{O}(\varepsilon^{-\bar{p}} \log(\varepsilon^{-1})^{\bar{p}+2}) & \text{if } d = \bar{p} \tau, \\ \mathcal{O}(\varepsilon^{-d/\tau} \log(\varepsilon^{-1})) & \text{if } d > \bar{p} \tau. \end{cases}$$

For $\bar{p} \in (\max\{1, d/(\hat{\beta} - 1)\}, 2]$ assuming $d < 2(\hat{\beta} - 1)$ and an error threshold $\varepsilon > 0$, we obtain

$$\sqrt{\mathbb{E}^{\mathbf{A}}(|\mathbb{E}(G(u)) - Q_L^{\text{RS}}(G(u^L))|^2)} = \mathcal{O}(\varepsilon)$$

and

$$\text{work} = \begin{cases} \mathcal{O}(\varepsilon^{-\bar{p}}) & \text{if } d < \bar{p}\tau, \\ \mathcal{O}(\varepsilon^{-\bar{p}} \log(\varepsilon^{-1})^{\bar{p}/2+2}) & \text{if } d = \bar{p}\tau, \\ \mathcal{O}(\varepsilon^{-d/\tau} \log(\varepsilon^{-1})) & \text{if } d > \bar{p}\tau. \end{cases}$$

Remark 9. The parameter choices for θ and $(s_\ell)_{\ell \geq 0}$ in Theorem 4 reflect *Strategy 1*. For *Strategy 2*, the assumptions $\bar{p} > d/(\min\{\hat{\beta} - \tau, \hat{\beta} - 1\})$, $\hat{\beta} > \tau$ are required, which is more restrictive if $\tau > 1$. However, aligning MRA and FE meshes might be useful in certain cases. Note that the truncation dimension in *Strategy 2* could also be capped as in *Strategy 1*, which may be beneficial in some cases. Adopting this strategy would affect the work measure only by a constant factor.

7 Numerical experiments

To illustrate the foregoing asymptotic error bounds, we consider a model diffusion equation of the form (1) in $d = 1$ spatial dimensions with parametric coefficient $a(x, \mathbf{y})$ and constant right hand side $f(x) = 10x$,

$$-(a(x, \mathbf{y})u'(x, \mathbf{y}))' = f \text{ in } D = (0, 1), \quad u(0, \mathbf{y}) = u(1, \mathbf{y}) = 0. \quad (30)$$

We model the dependence of the coefficient $a(x, \mathbf{y})$ on the parameters in terms of the affine parametrization (3) with $\bar{a}(x) \equiv 1$,

$$a(x, \mathbf{y}) = \bar{a}(x) + \sum_{j \geq 1} y_j \psi_j(x),$$

where we assume $\psi_j = \Psi_{j(\ell, k)}$ to be a system of continuous, piecewise linear spline wavelets for $\ell \geq 0$, $k = 1, \dots, 2^\ell$ with support overlap $K = 2$, see e.g. [16, Ch. 12]. Truncating at some level $L < \infty$ such that $\ell = 0, 1, \dots, L$ implies dimension truncation of the sum after dimension $s_L = 2^{L+1} - 1$. We pursue *Strategy 2* from Section 6, which yields for $\hat{\alpha} > \hat{\beta} > \tau$ a QMC weight sequence of the form

$$b_{j(\ell, k)} = \left(1 + c_2 2^{\hat{\beta}\ell}\right)^{-(\hat{\beta}-\tau)/\hat{\beta}},$$

for $0 < c_2 \in \mathbb{R}$ as specified in (25) (see also Remark 8). We use the implementation from [8] for applying the single-level and multilevel methods in parallel, and use Walsh coefficient bound $C = 0.1$ in component-by-component (CBC) construction, cp. [11] for details.

As goal functional, we consider point evaluation of the solution at $\bar{x} = e^{-1}$ (which is not a node on any mesh used in our simulations), $G(u(\cdot, \mathbf{y})) = u(\bar{x}, \mathbf{y})$, which implies the FE convergence rate $\tau = 1.5 - \varepsilon$ for arbitrary $\varepsilon > 0$. The parameter calibration will be done under the formal case $\tau = 1.5$. For a given discretization level ℓ , we solve the PDE (30) with the finite element method using piecewise linear basis functions on an equidistant mesh with meshwidth $h_\ell = 2^{-\ell-1}$. Considering

the wavelet basis for the coefficients on the same mesh, we obtain $s_\ell = h_\ell^{-1} - 1 = 2^{\ell+1} - 1$ parametric dimensions on level ℓ . We assume in the following the scaling $\|\psi_{j(\ell,k)}\|_{L^\infty(D)} = \sigma 2^{-\hat{\alpha}\ell}$, where we choose $\hat{\alpha} = 3$, $\hat{\beta} = 2.99$, $\sigma = 0.15$, yielding the expected QMC convergence rate $\hat{\beta} - \tau = 1.49$. For the multilevel method, we choose $N_\ell = 2^{m_\ell}$, where m_ℓ follows from (26). Also choose the limiting value for \bar{p} implies $\bar{p}^{-1} = \hat{\beta} - \tau \approx \tau$ which simplifies the resulting expression that is given by

$$m_\ell = \left\lceil L + \frac{2\tau + 1}{\tau(\tau + 1)} \log_2(L + 1) + \frac{1}{1 + \tau} (-\ell(1 + \tau) - \log_2(\ell + 1)) \right\rceil,$$

with $m_\ell = 1$ if the expression is not positive. This choice is based on the cost model

$$W_L = \sum_{\ell=0}^L N_\ell h_\ell^{-1} \log_2(s_\ell),$$

which we use for computing the cost in the multilevel experiment below. We compare the multilevel computations to a single-level approach, where we equilibrate the QMC and FEM discretization errors, yielding on a fixed level L with $N_L^{-1/\bar{p}} \sim h_L^\tau$ the choice $N_L = 2^{L+1}$,

$$m_L = L + 1.$$

In the single-level case, the work is simply $W_L^{SL} = N_L h_L^{-1} \log_2(s_L)$. We use the same generating vectors as above for the single-level method; this is justified since the weight sequence used in the CBC construction majorizes the weight sequence for the single level quadrature, theoretically capping the rate at $N^{-1.5}$. With these generating vectors, as observed in Figure 2, the measured QMC convergence rate is independent of the parameter dimension, and equals $N^{-\alpha}$ for $\alpha = 2, 3$ rather than the expected rate $N^{-1.5}$.

8 Conclusions

We provided the convergence rate analysis of randomly shifted and high order, interlaced polynomial lattice rules for the numerical evaluation of linear functionals G of solutions of countably affine-parametric, linear second order elliptic partial differential equations. The spatially inhomogeneous diffusion coefficient was assumed to be represented by a multiresolution analysis (MRA) with local supports, rather than the globally supported Karhunen-Loève expansion considered, for example, in [19, 6, 5, 14] and the references there. As in the corresponding single level QMC Petrov Galerkin approaches considered in [10], we proved that QMC with product weights, originally proposed by I. H. Sloan and H. Woźniakowski in [26], can provide optimal QMC convergence rates which are independent of the parameter dimension, unlike the so-called *product and order dependent (POD) weights* which are mandated by globally supported representation systems of uncertain input data. This, in turn,

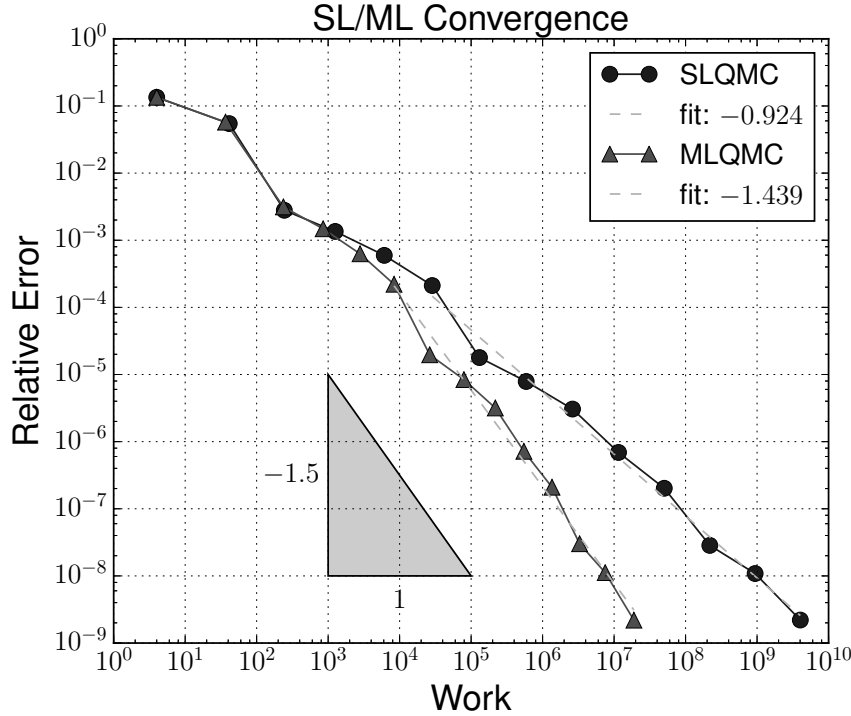


Fig. 1 Convergence of single-level and multilevel methods for a diffusion coefficient given in wavelet representation. As a reference solution, the multilevel approximation on the level $L = 14$ with a total of $s_L = 32767$ dimensions was used. The measured rates were obtained by a linear least squares fit on the last 9 points. The expected rates are -0.75 for SLQMC and -1.5 for MLQMC. The work is $W_L^{ML} = \sum_{\ell=0}^L N_\ell h_\ell^{-1} \log_2(s_\ell)$ for multilevel and $W_L^{SL} = N_L h_L^{-1} \log_2(s_L)$ for single-level.

results in linear w.r. to dimension scaling of fast CBC constructions from [22, 21], which originate in a dimension-wise, greedy strategy to minimize the worst case error, as proposed originally in [26]. The present analysis addressed linear, affine parametric random input data where the supports of the parameters are bounded. The extension for log-gaussian diffusion coefficients in the present setting, along the lines of [14, 17] (where the case of globally supported ψ_j were treated) and in the setting of the single level analysis in [15], will be given [9]. Numerical experiments were given for a model, linear elliptic problem in one space dimension. The present conclusions and findings hold, however, also for PDEs in multiple space dimension. Analogous error bounds for product weight QMC also hold for log-Gaussian representations of uncertain PDE inputs. Details on the corresponding error analysis, as well as numerical experiments, will be presented in [9].

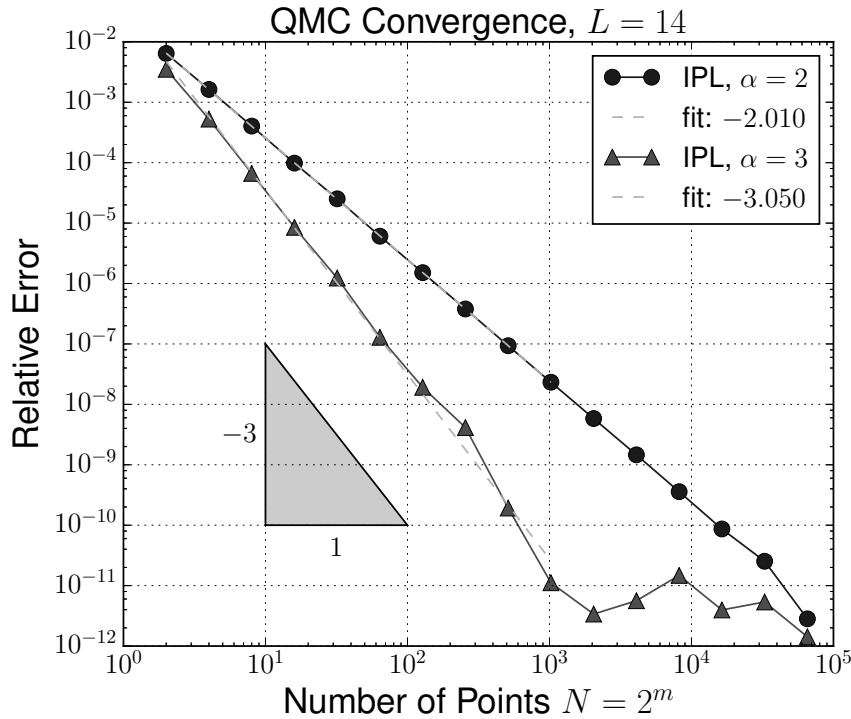


Fig. 2 Convergence of the QMC approximation using interlaced polynomial lattice (IPL) rules with $N = 2^m$ points, $m = 1, \dots, 17$ and for digit interlacing factors $\alpha = 2, 3$. We use the results with $m = 17$ as the reference value and keep the maximal discretization level $L = 14$ fixed, resulting in $s_L = 2^{15} - 1 = 32767$ parameter dimensions and smallest FEM meshwidth $h_L = 2^{-15}$.

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