

Adaptive PBDW approach to state estimation: noisy observations; user-defined update spaces

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Abstract

We provide a number of extensions and further interpretations of the Parameterized-Background Data-Weak (PBDW) formulation, a real-time and in-situ Data Assimilation (DA) framework for physical systems modeled by parametrized Partial Differential Equations (PDEs), proposed in [Y Maday, AT Patera, JD Penn, M Yano, Int J Numer Meth Eng, 102(5), 933-965]. Given M noisy measurements of the state, PBDW seeks an approximation of the form $u^* = z^* + \eta^*$, where the *background* z^* belongs to a N -dimensional *background space* informed by a parameterized mathematical model, and the *update* η^* belongs to a M -dimensional *update space* informed by the experimental observations. The contributions of the present work are threefold: first, we extend the adaptive formulation proposed in [T Taddei, M2AN, 51(5), 1827-1858] to general linear observation functionals, to effectively deal with noisy observations; second, we consider an user-defined choice of the update space, to improve convergence with respect to the number of measurements; third, we propose an *a priori* error analysis for general linear functionals in the presence of noise, to identify the different sources of state estimation error and ultimately motivate the adaptive procedure. We present results for two synthetic model problems in Acoustics, to illustrate the elements of the methodology and to prove its effectiveness. We further present results for a synthetic problem in Fluid Mechanics to demonstrate the applicability of the approach to vector-valued fields.

Keywords: variational data assimilation; parametrized partial differential equations; model order reduction; design of experiment.

1 Introduction

Data Assimilation (DA) refers to the process of integrating information coming from a (possibly parameterized) mathematical model with experimental observations, for prediction. State estimation is a particular DA task in which the Quantity of Interest (QOI) is the state u^{true} of a physical system over a domain of interest $\Omega \subset \mathbb{R}^d$. In this work, we propose a number of extensions, and further interpretations, of the Parameterized-Background Data-Weak (PBDW) approach to state estimation, first presented in [1].

As in [2], we denote by $\{y_m\}_{m=1}^M$ the set of experimental measurements, and we denote by $u^{\text{bk}}(\mu) \in \mathcal{X}$ the solution to the parameterized best-knowledge (bk)

mathematical model for the parameter value $\mu \in \mathcal{P}^{\text{bk}}$, $G^{\text{bk},\mu}(u^{\text{bk}}(\mu)) = 0$. Here, the space $\mathcal{X} = \mathcal{X}(\Omega)$ is a suitable Hilbert space defined over Ω , $G^{\text{bk},\mu}(\cdot)$ denotes the parameterized bk mathematical model associated with the physical system, and $\mathcal{P}^{\text{bk}} \subset \mathbb{R}^P$ reflects the uncertainty in the value of the parameters of the model. We here consider measurements of the form $y_m = \ell_m^o(u^{\text{true}}) + \epsilon_m$, where ℓ_m^o is a local average of the state about the location x_m^{obs} in Ω , and ϵ_m reflects the observational noise. On the other hand, the uncertainty in the parameters of the model leads to the definition of the bk manifold $\mathcal{M}^{\text{bk}} := \{u^{\text{bk}}(\mu)|_{\Omega} : \mu \in \mathcal{P}^{\text{bk}}\} \subset \mathcal{X}$ which collects the solution to the parameterized bk model for all values of the parameter in \mathcal{P}^{bk} , restricted to the domain of interest Ω . Since in practice the model is affected by non-parameterized (unanticipated) uncertainty, the true field does not in general belong to \mathcal{M}^{bk} .

The key idea of the PBDW formulation is to seek an approximation $u^* = z^* + \eta^*$ to the true field u^{true} employing projection-by-data. The first contribution to u^* , $z^* \in \mathcal{Z}_N$, is the *deduced background estimate*. The linear N -dimensional space $\mathcal{Z}_N \subset \mathcal{X}$ is informed by the bk manifold \mathcal{M}^{bk} : it thus encodes — in a mathematically-convenient way — the available prior knowledge about the system coming from the model. The second contribution to u^* , $\eta^* \in \mathcal{U}_M$, is the *update estimate*. The linear M -dimensional space \mathcal{U}_M is the span of the Riesz representer of the M observation functionals $\{\ell_m^o\}_{m=1}^M$: \mathcal{U}_M improves the approximation properties of the search space associated with the state estimation procedure. From a modelling perspective, the deduced background z^* addresses the parameterized uncertainty in the bk model, while the update addresses the non-parametric or unanticipated uncertainty. In [1], for perfect measurements ($\epsilon_m = 0$ for $m = 1, \dots, M$), the pair $(z^*, \eta^*) \in \mathcal{Z}_N \times \mathcal{U}_M$ is computed by searching for η^* of minimum norm subject to the observation constraints $\ell_m^o(z^* + \eta^*) = y_m$ for $m = 1, \dots, M$. In [2], for pointwise noisy measurements, the pair (z^*, η^*) is computed by solving a suitable Tikhonov regularization of the original constrained minimization statement proposed in [1].

PBDW provides some new contributions. First, the variational formulation facilitates the construction of *a priori* error estimates, which might guide the optimal choice of the experimental observations. Second, the background space \mathcal{Z}_N accommodates anticipated uncertainty associated with the parameters of the model in a computationally-convenient way; the construction of \mathcal{Z}_N based on \mathcal{M}^{bk} relies on the application of parametric Model Order Reduction (pMOR) techniques. Third, unlike standard least-squares methods, PBDW provides a mechanism — the update η^* — to correct the deficiencies of the bk model. Finally, projection-by-data, as opposed to projection-by-model, simplifies the treatment of uncertainty in boundary conditions, particularly when the mathematical model is defined over a domain Ω^{bk} that strictly contains Ω ([3]). We remark that several of these ingredients have appeared in different contexts: we refer to [1, 4, 2] for a thorough overview of the links between the PBDW formulation and other DA techniques, and to [5] for a thorough introduction to Data Assimilation.

In this work, we propose three contributions to the original PBDW formulation.

1. We extend the adaptive formulation proposed in [2] for pointwise measurements to general linear observation functionals. The approach reads

as a Tikhonov regularization of the constrained minimization statement in [1], and can also be interpreted as a convex relaxation of the Partial Spline Model ([6, Chapter 9]).

2. In [1], the update space \mathcal{U}_M is induced by the particular inner product chosen for \mathcal{X} (*variational update*); in this work, we propose to first choose the space \mathcal{U}_M , and then recover the variational formulation through the definition of a suitable inner product (*user-defined update*). We demonstrate that our choice reduces the offline costs, and improves the approximation properties of the update space for smooth fields. We emphasize that the idea of selecting the approximation space before introducing the inner products is widely used in the kernel methods' literature (see, e.g., [7]) for pointwise measurements, and has already been exploited in [2].
3. We propose an *a priori* error analysis for general linear functionals in the presence of noise. First, we present a bound for the deterministic error between u^{true} and the PBDW solution u^{opt} , fed with perfect measurements. Then, we present a bound for the stochastic error between the possibly regularized PBDW solution u^* fed with imperfect (noisy) measurements, and the PBDW solution u^{opt} , fed with perfect measurements. The idea of identifying different sources of error and deriving distinct bounds for each source is the same exploited in [8], for the estimate of the state estimation error based on local measurements of the state.

The outline of the paper is as follows. In section 2, we present the methodology: we review the derivation of the adaptive PBDW formulation for noisy measurements as discussed in [9]; we introduce the user-defined update space, and we discuss its variational interpretation; we discuss the selection of the observation functionals; we present an adaptive procedure for the selection of the hyper-parameter associated with the Tikhonov regularizer; and we discuss the extension to vector-valued problems. In section 3, we present an *a priori* error analysis for noisy measurements for the state estimation error. In section 4 we present results for two synthetic model problems in Acoustics, to illustrate the elements of the methodology and to prove its effectiveness. Finally, in section 5, we consider a synthetic Fluid Mechanics model problem to demonstrate the applicability of PBDW to vector-valued problems.

2 Formulation

2.1 Preliminaries

Given the Lipschitz domain $\Omega \subset \mathbb{R}^d$, we introduce the Hilbert space \mathcal{X} defined over Ω ; we endow \mathcal{X} with the inner product (\cdot, \cdot) and the induced norm $\|\cdot\| = \sqrt{(\cdot, \cdot)}$. We further denote by \mathcal{X}' the dual space of \mathcal{X} . For any closed linear subspace $\mathcal{Q} \subset \mathcal{X}$, we denote by $\Pi_{\mathcal{Q}} : \mathcal{X} \rightarrow \mathcal{Q}$ the orthogonal projection operator onto \mathcal{Q} , and we denote by \mathcal{Q}^{\perp} its orthogonal complement. Given the linear functional $\ell \in \mathcal{X}'$, we denote by $R_{\mathcal{X}}\ell \in \mathcal{X}$ the corresponding Riesz element, $(R_{\mathcal{X}}\ell, f) = \ell(f)$ for all $f \in \mathcal{X}$.

Given a random variable X , we denote by $\mathbb{E}[X]$ and by $\mathbb{V}[X]$ the mean and the variance, where \mathbb{E} denotes expectation. We denote by $X \sim \mathcal{N}(m, \sigma^2)$ a

Gaussian random variable with mean m and variance σ^2 . Similarly, we denote by $X \sim \text{Uniform}(\Omega)$ an uniform random variable over Ω . Furthermore, we refer to an arbitrary random variable ε such that $\mathbb{E}[\varepsilon] = 0$ and $\mathbb{V}[\varepsilon] = \sigma^2$ using the notation $\varepsilon \sim (0, \sigma^2)$.

We state upfront that in this section, we limit ourselves to real-valued problems; however, the discussion can be trivially extended to the complex-valued case. Furthermore, in sections 2.2 — 2.7, we consider scalar fields; then, in section 2.8, we discuss the extension to vector-valued problems.

2.2 Derivation of the PBDW statement

As explained in the introduction, we aim to estimate the deterministic state $u^{\text{true}} \in \mathcal{X}$ over the domain of interest $\Omega \subset \mathbb{R}^d$. We shall afford ourselves two sources of information: a bk mathematical model

$$G^{\text{bk}, \mu}(u^{\text{bk}}(\mu)) = 0, \quad \mu \in \mathcal{P}^{\text{bk}}$$

defined over a domain Ω^{bk} that contains Ω ; and M experimental observations y_1, \dots, y_M such that

$$y_m = \ell_m^o(u^{\text{true}}) + \epsilon_m, \quad m = 1, \dots, M,$$

where $\ell_1^o, \dots, \ell_M^o \in \mathcal{X}'$ are suitable observation functionals, and $\{\epsilon_m\}_{m=1}^M$ are unknown disturbances caused by either systematic error in the data acquisition system or experimental random noise. Here, $\mathcal{P}^{\text{bk}} \subset \mathbb{R}^P$ is a confidence region for the true values of the parameters of the model. We further introduce the bk manifold $\mathcal{M}^{\text{bk}} = \{u^{\text{bk}}(\mu)|_{\Omega} : \mu \in \mathcal{P}^{\text{bk}}\}$ associated with the solution to the parameterized model for all values of the parameters in \mathcal{P}^{bk} , restricted to the domain of interest Ω .

In order to combine the parameterized model with the experimental observations, Wahba proposed the following generalization of the 3D-VAR ([10, 11]) statement for parameterized background, known as Partial Spline Model ([6, Chapter 9]): find the state estimate $u_{\xi}^* = u^{\text{bk}}(\mu_{\xi}^*) + \eta_{\xi}^*$ such that

$$(\mu_{\xi}^*, \eta_{\xi}^*) := \arg \min_{(\mu, \eta) \in \mathcal{P}^{\text{bk}} \times \mathcal{U}} \xi \|\eta\|^2 + V_M(\mathcal{L}_M(u^{\text{bk}}(\mu) + \eta) - \mathbf{y}); \quad (1)$$

where $\xi > 0$ is a tuning hyper-parameter, $\mathbf{y} = [y_1, \dots, y_M]$ is the vector of experimental observations, $\mathcal{L}_M(u) = [\ell_1^o(u), \dots, \ell_M^o(u)]$, and $V_M : \mathbb{R}^M \rightarrow \mathbb{R}_+$ is a suitable strictly convex loss function with minimum in $\mathbf{0}$ that will be specified later. Finally, \mathcal{U} is the *search space*: \mathcal{U} is a closed linear subspace contained in \mathcal{X} that will be specified in the next section. We observe that (1) is non-convex in μ ; furthermore, evaluations of the map $\mu \mapsto u^{\text{bk}}(\mu)$ involve the solution to the bk model. Therefore, (1) is not suitable for real-time computations.

If we introduce the rank- N approximation ([12]) of the bk field $u^{\text{bk}}(\mu)$,

$$u_N^{\text{bk}}|_{\Omega}(x, \mu) = \sum_{n=1}^N z_n(\mu) \zeta_n(x), \quad x \in \Omega, \quad \mu \in \mathcal{P}^{\text{bk}},$$

we can approximate statement (1) as

$$(\mu_{\xi}^*, \eta_{\xi}^*) := \arg \min_{(\mu, \eta) \in \mathcal{P}^{\text{bk}} \times \mathcal{U}} \xi \|\eta\|^2 + V_M \left(\mathcal{L}_M \left(\sum_{n=1}^N z_n(\mu) \zeta_n + \eta \right) - \mathbf{y} \right). \quad (2)$$

Assuming that we are not interested in the estimate of the parameter μ_ξ^* , (2) is equivalent to:

$$(\mathbf{z}_\xi^*, \eta_\xi^*) = \arg \min_{(\mathbf{z}, \eta) \in \Phi_N \times \mathcal{U}} \xi \|\eta\|^2 + V_M \left(\mathcal{L}_M \left(\sum_{n=1}^N z_n \zeta_n + \eta \right) - \mathbf{y} \right) \quad (3)$$

where $\Phi_N = \{[z_1(\mu), \dots, z_N(\mu)] : \mu \in \mathcal{P}^{\text{bk}}\} \subset \mathbb{R}^N$ is the image of the parameter-dependent coefficients, and the corresponding state estimate is given by $u_\xi^* = \sum_{n=1}^N (\mathbf{z}_\xi^*)_n \zeta_n + \eta_\xi^*$.

The set Φ_N in (3) is non-convex; therefore, we convexify (3) by minimizing the objective over the convex approximation of Φ_N , $\tilde{\Phi}_N$:

$$(\mathbf{z}_\xi^*, \eta_\xi^*) = \arg \min_{(\mathbf{z}, \eta) \in \tilde{\Phi}_N \times \mathcal{U}} \xi \|\eta\|^2 + V_M \left(\mathcal{L}_M \left(\sum_{n=1}^N z_n \zeta_n + \eta \right) - \mathbf{y} \right) \quad (4)$$

We refer to (4) as to the PBDW formulation: the formulation generalizes the statements introduced in [1, 4, 2].

In this work, we study the following instance of the general PBDW formulation:

$$(\mathbf{z}_\xi^*, \eta_\xi^*) = \arg \min_{(\mathbf{z}, \eta) \in \mathbb{R}^N \times \mathcal{U}} \xi \|\eta\|^2 + \frac{1}{M} \|\mathcal{L}_M \left(\sum_{n=1}^N z_n \zeta_n + \eta \right) - \mathbf{y}\|_2^2,$$

which can also be reformulated as follows:

$$(\mathbf{z}_\xi^*, \eta_\xi^*) := \arg \inf_{(\mathbf{z}, \eta) \in \mathcal{Z}_N \times \mathcal{U}} J_\xi(\mathbf{z}, \eta) := \xi \|\eta\|^2 + \frac{1}{M} \|\mathcal{L}_M(\mathbf{z} + \eta) - \mathbf{y}\|_2^2, \quad (5)$$

where $\mathcal{Z}_N = \text{span}\{\zeta_n\}_{n=1}^N \subset \mathcal{X}$ is called the *background space*. In the limit $\xi \rightarrow 0^+$, the formulation reduces to ([9, Proposition 2.5.1]):

$$(\mathbf{z}_\xi^*, \eta_\xi^*) := \arg \inf_{(\mathbf{z}, \eta) \in \mathcal{Z}_N \times \mathcal{U}} \|\eta\|, \quad \text{subject to } \mathcal{L}_M(\mathbf{z} + \eta) = \mathbf{y}; \quad (6)$$

which corresponds to the original formulation proposed in [1].

Some comments are in order. The choice of the loss function V_M should be based on the expected experimental disturbances: the particular form considered here is appropriate for homoscedastic noise ($\epsilon_1, \dots, \epsilon_M$ are independent realizations of the random variable $\epsilon \sim (0, \sigma^2)$). Furthermore, as observed in [13] in a related framework, the relaxation $\tilde{\Phi}_N = \mathbb{R}^N$ might lead to stability issues for $N \simeq M$. We refer to a future work for the analysis of more general losses and for tighter relaxations $\tilde{\Phi}_N$ of Φ_N . The hyper-parameter ξ is selected adaptively, based on hold-out validation as in [2]; for completeness, in section 2.7, we summarize the validation procedure.

2.3 Choice of \mathcal{U} : variational and user-defined update spaces

We consider two choices for the search space \mathcal{U} : (i) $\mathcal{U} = \mathcal{X}$; and (ii) $\mathcal{U} = \text{span}\{\psi_m\}_{m=1}^M$ where $\psi_1, \dots, \psi_M \in \mathcal{X}$ are linearly independent user-defined functions satisfying the unisolvency condition:

$$\psi \in \mathcal{U}_M, \ell_m^o(\psi) = 0, \quad m = 1, \dots, M \quad \Leftrightarrow \quad \psi \equiv 0. \quad (7)$$

The first choice is considered in the original PBDW papers, while the second choice is proposed here for the first time.

As shown in [9, Proposition 2.2.3] for (5), for $\mathcal{U} = \mathcal{X}$, the update η_ξ^* belongs to the update space $\mathcal{U}_M = \text{span}\{R_{\mathcal{X}}\ell_m^o\}_{m=1}^M$; we refer to this choice of the update space \mathcal{U}_M (or equivalently of \mathcal{U}) as to *variational update*. If $\ell_1^o, \dots, \ell_M^o$ are linearly independent in \mathcal{X}' , it is easy to verify that the space \mathcal{U}_M satisfies (7). Computation of the update space \mathcal{U}_M requires the solution to M variational problems, and depends on the choice of the inner product (\cdot, \cdot) of \mathcal{X} , and on the observation functionals $\ell_1^o, \dots, \ell_M^o$.

We refer to the second choice $\mathcal{U}_M = \mathcal{U} = \text{span}\{\psi_m\}_{m=1}^M$ as *user-defined update*. The functions ψ_1, \dots, ψ_M are chosen based on approximation considerations, to guarantee fast convergence with respect to the number of measurements. We observe that \mathcal{U}_M mildly depends on the observation functionals — it should satisfy (7) — but it does not depend on the choice of the inner product (\cdot, \cdot) of \mathcal{X} . In particular, computation of the user-defined update does not in principle require the solution to any variational problem: we might thus rely on user-defined updates to simplify the implementation of the method. It is possible to recover a variational interpretation for this update space for a suitable inner product of \mathcal{X} : we discuss this point in section 2.4.

Practical choice of the update space

As explained in the introduction, we are interested in experimental observations that can be modelled by linear functionals of the form

$$\ell_m^o(u) = \ell(u, x_m^{\text{obs}}, r_w) = C(x_m^{\text{obs}}) \int_{\Omega} \omega\left(\frac{1}{r_w} \|x - x_m^{\text{obs}}\|_2\right) u(x) dx, \quad (8)$$

where r_w reflects the filter width of the transducer, x_m^{obs} denotes the transducer location, and ω describes the local averaging process performed by the experimental device. For this class of observation functionals, we consider updates of the form

$$\mathcal{U}_M = \text{span}\{\phi(\cdot, x_m^{\text{obs}})\}_{m=1}^M.$$

where $\phi(\cdot, x_m^{\text{obs}}) = R_{\mathcal{X}}\ell(\cdot, x_m^{\text{obs}}, r_w)$ (variational update), or ϕ might be an user-defined function. We refer to ϕ as to *update generator*.

If \mathcal{X} is the free space $H^s(\Omega)$ for some $s \geq 1$, we might consider the generator

$$\phi(\cdot, x) = \Phi(\|\cdot - x\|_2), \quad (9)$$

where $\Phi: \mathbb{R}_+ \rightarrow \mathbb{R}_+$ is a positive definite kernel Φ (see, e.g., [7]). Computation of (9) does not require the solution to any variational procedure, and for small values of r_w it leads to superior approximation properties compared to the standard H^1 variational update, as we will demonstrate in the numerical results. Another potential choice is to consider:

$$\phi(\cdot, x) = R_{\mathcal{X}}\ell(\cdot, x, R_w), \quad (10)$$

for some $R_w > r_w$. The generator (10) requires the solution to M variational problems during the offline stage (as opposed to (9)); on the other hand, it permits the imposition of homogeneous Dirichlet boundary conditions¹.

¹ Homogeneous Dirichlet boundary conditions could be imposed using the generator (9) by

2.4 Variational interpretation of the user-defined space, and well-posedness analysis

Given the update space $\mathcal{U}_M \subset \mathcal{X}$, we introduce the interpolation operator $\mathcal{I}_M : \mathcal{X} \rightarrow \mathcal{U}_M$ s.t. $\ell_m^o(\mathcal{I}_M(u)) = \ell_m^o(u)$ for all $u \in \mathcal{X}$, $m = 1, \dots, M$. Then, we define the symmetric bilinear form

$$((u, v)) = (u - \mathcal{I}_M(u), v - \mathcal{I}_M(v)) + (\mathcal{I}_M(u), \mathcal{I}_M(v)). \quad (11)$$

The bilinear form (11) and the induced (semi-)norm $\|\cdot\| = \sqrt{(\cdot, \cdot)}$ satisfy the following properties.

Lemma 2.1. *Let $\mathcal{U}_M = \text{span}\{\psi_m\}_{m=1}^M$ be an M -dimensional space satisfying (7), where ψ_1, \dots, ψ_M are orthonormal. Then, the following hold.*

1. $\|u\| = \|u\| \quad \forall u \in \mathcal{U}_M$.
2. *Given the orthonormal basis ψ_1, \dots, ψ_M of \mathcal{U}_M , we define $\mathbb{L}_\eta \in \mathbb{R}^{M,M}$ such that $(\mathbb{L}_\eta)_{m,m'} = \ell_m(\psi_{m'})$. Then, we can rewrite (11) as follows:*

$$((u, v)) = (u - \mathcal{I}_M(u), v - \mathcal{I}_M(v)) + \sum_{m,m'=1}^M \ell_m^o(u) \ell_{m'}^o(v) \mathbb{W}_{m,m'}, \quad (12)$$

where $\mathbb{W} := \mathbb{L}_\eta^{-T} \mathbb{L}_\eta^{-1}$.

3. *The bilinear form $((\cdot, \cdot))$ induces a norm over \mathcal{X} . More precisely, the following estimate holds:*

$$\frac{1}{2} \|u\|^2 \leq \|u\|^2 \leq \left(2 + 3 \|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}^2\right) \|u\|^2, \quad \|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})} = \sup_{v \in \mathcal{X}} \frac{\|\mathcal{I}_M(v)\|}{\|v\|}. \quad (13)$$

4. *Let $\phi_m = \sum_{p=1}^M (\mathbb{L}_\eta)_{m,p} \psi_p$. Then, $((\phi_m, v)) = \ell_m^o(v)$ for all $v \in \mathcal{X}$.*
5. *If $\mathcal{U}_M = \text{span}\{R_{\mathcal{X}} \ell_m^o\}_{m=1}^M$, then $((\cdot, \cdot)) = (\cdot, \cdot)$.*
6. $\Pi_{\mathcal{U}_M}^{\|\cdot\|} u = \mathcal{I}_M(u)$ for all $u \in \mathcal{X}$.

Proof. If $u \in \mathcal{U}_M$, $\mathcal{I}_M(u) = u$. Therefore,

$$\|u\|^2 = (u - \mathcal{I}_M(u), u - \mathcal{I}_M(u)) + (\mathcal{I}_M(u), \mathcal{I}_M(u)) = (u, u) = \|u\|^2,$$

which proves the first statement.

Observing that $\mathcal{I}_M(u) = \sum_{m=1}^M (\mathbb{L}_\eta^{-1} \mathcal{L}_M(u))_m \psi_m$, and recalling that ψ_1, \dots, ψ_M are orthonormal, we find

$$\begin{aligned} (\mathcal{I}_M(u), \mathcal{I}_M(v)) &= \sum_{m,m'=1}^M (\mathbb{L}_\eta^{-1} \mathcal{L}_M(u))_m (\mathbb{L}_\eta^{-1} \mathcal{L}_M(v))_{m'} (\psi_m, \psi_{m'}) \\ &= \sum_{m=1}^M (\mathbb{L}_\eta^{-1} \mathcal{L}_M(u))_m (\mathbb{L}_\eta^{-1} \mathcal{L}_M(v))_m = \sum_{p,p'=1}^M \ell_p^o(u) \ell_{p'}^o(v) \mathbb{W}_{p,p'}, \end{aligned}$$

adding measurements on the Dirichlet boundary: this approach increases the dimensionality M of the update space, and thus it increases the online cost associated with the computation of the state estimate.

which proves the second statement.

We now prove (13) (cf. statement 3). First, we find that

$$\|u\|^2 \leq 2(\|u - \mathcal{I}_M(u)\|^2 + \|\mathcal{I}_M(u)\|^2) = 2\|u\|^2,$$

where the first inequality follows from the triangular inequality and $(a+b)^2 \leq 2a^2 + 2b^2$, while the second identity follows directly from the definition of $((\cdot, \cdot))$. Second, exploiting the fact that the interpolation operator is continuous in \mathcal{X} , we find

$$\|u\|^2 = \|u - \mathcal{I}_M(u)\|^2 + \|\mathcal{I}_M(u)\|^2 \leq 2\|u\|^2 + 3\|\mathcal{I}_M(u)\|^2 \leq \left(2 + 3\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}^2\right) \|u\|^2.$$

Combining the latter two estimates, we obtain (13).

We prove the fourth statement. Since $\phi_m \in \mathcal{U}_M$, $\phi_m - \mathcal{I}_M(\phi_m) \equiv 0$. Therefore,

$$((\phi_m, v)) = \sum_{p,p'=1}^M \ell_p^o(\phi_m) \ell_{p'}^o(v) \mathbb{W}_{p,p'}.$$

By definition of the interpolation operator, we have $\ell_{p'}^o(v) = \ell_{p'}^o(\mathcal{I}_M(v))$ for $p' = 1, \dots, M$, and $\mathcal{I}_M(v) = \sum_{k'=1}^M (\mathbb{L}_\eta^{-1} \mathcal{L}_M(v))_{k'} \psi_{k'}$. Then, we find

$$\begin{aligned} ((\phi_m, v)) &= \sum_{k,k'=1}^M \sum_{p,p'=1}^M (\mathbb{L}_\eta)_{m,k} \ell_p^o(\psi_k) \ell_{p'}^o(\psi_{k'}) \mathbb{W}_{p,p'} (\mathbb{L}_\eta^{-1} \mathcal{L}_M(v))_{k'} \\ &= \sum_{k,q=1}^M (\mathbb{L}_\eta)_{m,k} (\mathbb{L}_\eta^{-1})_{k,q} \ell_q^o(v) = \sum_{q=1}^M (\mathbb{L}_\eta \mathbb{L}_\eta^{-1})_{m,q} \ell_q^o(v) = \ell_m^o(v), \end{aligned}$$

for all $v \in \mathcal{X}$. Thesis follows.

In order to prove the fifth statement, we observe that, for $\mathcal{U}_M = \text{span}\{R_{\mathcal{X}} \ell_m^o\}_{m=1}^M$, $\mathcal{I}_M(u) = \Pi_{\mathcal{U}_M} u$. Then, exploiting the properties of $((\cdot, \cdot))$ shown so far and the projection theorem, we find

$$\|u\|^2 = \|u - \mathcal{I}_M(u)\|^2 + \|\mathcal{I}_M(u)\|^2 = \|\Pi_{\mathcal{U}_M^\perp}(u)\|^2 + \|\Pi_{\mathcal{U}_M}(u)\|^2 = \|u\|^2.$$

The proof the sixth statement follows directly from the fourth property:

$$((\Pi_{\mathcal{U}_M}^{\|\cdot\|} u, v)) = ((u, v)) \quad \forall v \in \mathcal{U}_M \Leftrightarrow \ell_m^o(\Pi_{\mathcal{U}_M}^{\|\cdot\|} u) = \ell_m^o(v), \quad m = 1, \dots, M.$$

The latter completes the proof. \square

Remark 2.1. The norm $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ is the Lebesgue constant in the \mathcal{X} norm, and it is the inverse of the inf-sup constant ([14, Theorem 2.4]):

$$\gamma_M := \inf_{w \in \mathcal{U}_M} \sup_{v \in \mathcal{W}_M} \frac{(w, v)}{\|w\| \|v\|}, \quad \mathcal{W}_M = \text{span}\{R_{\mathcal{X}} \ell_m^o\}_{m=1}^M.$$

The Lebesgue constant depends on the triple $\mathcal{O} = (\{\ell_m^o\}_{m=1}^M, \mathcal{U}_M, (\mathcal{X}, \|\cdot\|))$. For certain choices of the triple \mathcal{O} , it is possible to determine the asymptotic behavior of $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$: to provide a concrete example, we refer to [15, Corollary 1.17] for an important result concerning the behavior of $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ for one-dimensional polynomial interpolation.

Lemma 2.1 can be exploited to recover an infinite-dimensional variational interpretation of the PBDW statement with user-defined update. The proof is a straightforward consequence of [9, Proposition 2.2.3], and is here omitted.

Proposition 2.1. *Let \mathcal{U}_M be an M -dimensional space satisfying (7); then, the PBDW solution to (5) for $\mathcal{U} = \mathcal{U}_M$ solves the following problem:*

$$(z_\xi^*, \eta_\xi^*) := \arg \inf_{(z, \eta) \in \mathcal{Z}_N \times \mathcal{X}} \xi \|\eta\|^2 + \frac{1}{M} \|\mathcal{L}_M(z + \eta) - \mathbf{y}\|_2^2, \quad (14)$$

where $\|\cdot\|$ is the norm induced by the inner product $((\cdot, \cdot))$ of \mathcal{X} defined in (11).

If the inf-sup constant ([1])

$$\beta_{N,M} = \inf_{z \in \mathcal{Z}_N} \sup_{q \in \mathcal{U}_M} \frac{((z, q))}{\|z\| \|q\|} \quad (15)$$

is strictly positive, then the solution (z_ξ^*, η_ξ^*) to (14) is unique, and solves the following saddle-point problem:

$$\begin{cases} 2\xi((\eta_\xi^*, q)) + \frac{2}{M} \sum_{m=1}^M \left(\ell_m^o(z_\xi^* + \eta_\xi^*) - y_m \right) \ell_m^o(q) &= 0 \quad \forall q \in \mathcal{U}_M; \\ ((\eta_\xi^*, p)) &= 0 \quad \forall p \in \mathcal{Z}_N. \end{cases} \quad (16)$$

Furthermore, the estimate u_ξ^* belongs to the space:

$$u_\xi^* \in \mathcal{Z}_N \oplus \mathcal{Z}_N^{\perp, \|\cdot\|} \cap \mathcal{U}_M = \{z + \eta : z \in \mathcal{Z}_N, \eta \in \mathcal{U}_M, ((\eta, q)) = 0 \quad \forall q \in \mathcal{Z}_N\};$$

where $\mathcal{Z}_N^{\perp, \|\cdot\|}$ denotes the orthogonal complement of \mathcal{Z}_N with respect to the $\|\cdot\|$ norm.

Remark 2.2. In the variational approach, we first choose an inner product (\cdot, \cdot) for \mathcal{X} , and then we appeal to an high-fidelity solver to generate the update space; on the other hand, in the user-defined approach, we first choose the space \mathcal{U}_M , and then we use it to define the inner product $((\cdot, \cdot))$ (11). We remark that the second approach is used in the kernel methods' literature (see, e.g., [7]) for pointwise measurements. Given a positive definite kernel is possible to characterize the Sobolev regularity of the resulting ambient (native) space: the characterization of the properties of the ambient space can be then exploited to prove a priori error bounds for the state estimation error, and estimate the asymptotic convergence rate as $M \rightarrow \infty$. On the other hand, the construction presented in this section does not allow us to characterize the smoothness of the space induced by the norm $\|\cdot\|$ in the limit $M \rightarrow \infty$, unless $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ is bounded for $M \rightarrow \infty$.

2.5 Algebraic formulation

Given the fields $z \in \mathcal{Z}_N$ and $\eta \in \mathcal{U}_M$, we introduce the vectors $\mathbf{z} \in \mathbb{R}^N$ and $\boldsymbol{\eta} \in \mathbb{R}^M$ such that $z = \sum_{n=1}^N z_n \zeta_n$, and $\eta = \sum_{m=1}^M \eta_m \psi_m$, where ζ_1, \dots, ζ_N and ψ_1, \dots, ψ_M are orthonormal bases (with respect to $\|\cdot\|$) of \mathcal{Z}_N and \mathcal{U}_M , respectively. We remark upfront that the derivation is independent of the particular construction of the update space. Then, we can rewrite (5) as a discrete optimization problem for the coefficients:

$$(\mathbf{z}_\xi^*, \boldsymbol{\eta}_\xi^*) = \arg \min_{(\mathbf{z}, \boldsymbol{\eta}) \in \mathbb{R}^N \times \mathbb{R}^M} \xi \|\boldsymbol{\eta}\|_2^2 + \frac{1}{M} \|\mathbb{L}_\eta \boldsymbol{\eta} + \mathbb{L}_z \mathbf{z} - \mathbf{y}\|_2^2; \quad (17)$$

where $\mathbb{L}_z \in \mathbb{R}^{M,N}$, and $\mathbb{L}_\eta \in \mathbb{R}^{M,M}$ are given by $(\mathbb{L}_z)_{m,n} = \ell_m^o(\zeta_n)$, $(\mathbb{L}_\eta)_{m,m'} = \ell_m^o(\psi_{m'})$. We observe that (7) implies that \mathbb{L}_η is invertible. By differentiating the objective function with respect to \mathbf{z} and $\boldsymbol{\eta}$, we obtain

$$\begin{cases} (\xi M\mathbb{I} + \mathbb{L}_\eta^T \mathbb{L}_\eta) \boldsymbol{\eta}_\xi^* + \mathbb{L}_\eta^T \mathbb{L}_z \mathbf{z}_\xi^* = \mathbb{L}_\eta^T \mathbf{y}; \\ \mathbb{L}_z^T \mathbb{L}_\eta \boldsymbol{\eta}_\xi^* + \mathbb{L}_z^T \mathbb{L}_z \mathbf{z}_\xi^* = \mathbb{L}_z^T \mathbf{y}. \end{cases} \quad (18)$$

If we multiply (18)₁ by $\mathbb{L}_z^T \mathbb{L}_\eta^{-T}$, and we exploit (18)₂ we obtain

$$\xi M \mathbb{L}_\eta^T \mathbb{L}_\eta^{-T} \boldsymbol{\eta}_\xi^* + \mathbb{L}_z^T \mathbb{L}_\eta \boldsymbol{\eta}_\xi^* + \mathbb{L}_z^T \mathbb{L}_z \mathbf{z}_\xi^* = \mathbb{L}_z^T \mathbf{y} = \mathbb{L}_z^T \mathbb{L}_\eta \boldsymbol{\eta}_\xi^* + \mathbb{L}_z^T \mathbb{L}_z \mathbf{z}_\xi^* \Rightarrow \mathbb{L}_z^T \mathbb{L}_\eta^{-T} \boldsymbol{\eta}_\xi^* = \mathbf{0}$$

Finally, if we introduce $\tilde{\boldsymbol{\eta}}_\xi^* = \mathbb{L}_\eta^{-T} \boldsymbol{\eta}_\xi^*$ and we multiply (18)₁ by \mathbb{L}_η^{-T} , we obtain

$$\begin{cases} (\xi M\mathbb{I} + \mathbb{L}_\eta \mathbb{L}_\eta^T) \tilde{\boldsymbol{\eta}}_\xi^* + \mathbb{L}_z \mathbf{z}_\xi^* = \mathbf{y}, \\ \mathbb{L}_z^T \tilde{\boldsymbol{\eta}}_\xi^* = \mathbf{0}; \end{cases} \quad \boldsymbol{\eta}_\xi^* = \mathbb{L}_\eta^T \tilde{\boldsymbol{\eta}}_\xi^*. \quad (19)$$

System (19) can be used to efficiently compute the PBDW solution.

Remark 2.3. (spectrum of the PBDW system) Following the argument in [16, Section 3.4], we observe that the saddle-point system (19) is congruent to the block-diagonal matrix $\begin{bmatrix} \mathbb{L}_\eta \mathbb{L}_\eta^T + \xi M\mathbb{I} & 0 \\ 0 & -\mathbb{L}_z^T (\mathbb{L}_\eta \mathbb{L}_\eta^T + \xi M\mathbb{I})^{-1} \mathbb{L}_z \end{bmatrix}$. If the update satisfies (7), \mathbb{L}_η is invertible, and thus $\mathbb{L}_\eta \mathbb{L}_\eta^T + \xi M\mathbb{I}$ is positive definite for all $\xi \geq 0$.

On the other hand, the second block $-\mathbb{L}_z^T (\mathbb{L}_\eta \mathbb{L}_\eta^T + \xi M\mathbb{I})^{-1} \mathbb{L}_z$ is negative definite if and only if the rank of \mathbb{L}_z is equal to N : this condition is equivalent to the positivity of $\beta_{N,M}$ in Proposition 2.1.

In view of the analysis of the method, and of the definition of the Greedy procedure for the selection of the transducers' location, next Proposition provides a computable expression for the inf-sup constant $\beta_{N,M}$ defined in (15), and for the norm $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ in (13).

Proposition 2.2. Suppose that ζ_1, \dots, ζ_N and ψ_1, \dots, ψ_M are orthonormal in $\|\cdot\|$. The inf-sup constant $\beta_{N,M}$ is the square root of the minimum eigenvalue of the following eigenproblem:

$$\mathbb{L}_z^T \mathbb{W} \mathbb{L}_z \mathbf{z}_n = \nu_n (\mathbb{I} + 2\mathbb{L}_z^T \mathbb{W} \mathbb{L}_z - 2\text{sym}(\mathbb{C}^T \mathbb{L}_\eta^{-1} \mathbb{L}_z)) \mathbf{z}_n, \quad n = 1, \dots, N; \quad (20)$$

while the norm $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ is the inverse of the square root of the minimum eigenvalue of the following eigenproblem:

$$\mathbb{L}_\eta^T \mathbb{K}^{-1} \mathbb{L}_\eta \boldsymbol{\eta}_m = \lambda_m \boldsymbol{\eta}_m, \quad m = 1, \dots, M. \quad (21)$$

Here, $\mathbb{W} = \mathbb{L}_\eta^{-T} \mathbb{L}_\eta^{-1}$, $\text{sym}(A) = \frac{1}{2}(A + A^T)$, while the matrices $\mathbb{C} \in \mathbb{R}^{M,N}$ and $\mathbb{K} \in \mathbb{R}^{M,M}$ are given by $\mathbb{C}_{m,n} = (\psi_m, \zeta_n)$, and $\mathbb{K}_{m,m'} = (R_{\mathcal{X}} \ell_m^o, R_{\mathcal{X}} \ell_{m'}^o)$.

Proof. Given $z = \sum_{n=1}^N z_n \zeta_n$, $\eta = \sum_{m=1}^M \eta_m \psi_m$, we can write the interpolation operator as $\mathcal{I}_M(z) = \sum_{k=1}^M (\mathbb{L}_\eta^{-1} \mathbb{L}_z \mathbf{z})_k \psi_k$. Then, we obtain

$$((z, \eta)) = \mathbf{z}^T \mathbb{L}_z^T \mathbb{W} \mathbb{L}_\eta \boldsymbol{\eta}, \quad \|\eta\|^2 = \boldsymbol{\eta}^T \boldsymbol{\eta};$$

and

$$\|z\|^2 = \|z\|^2 + \|\mathcal{I}_M(z)\|^2 - 2(z, \mathcal{I}_M(z)) + \mathbf{z}^T \mathbb{L}_z^T \mathbb{W} \mathbb{L}_z \mathbf{z} = \mathbf{z}^T \mathbb{B} \mathbf{z},$$

where $\mathbb{B} = \mathbb{I} + 2\mathbb{L}_z^T \mathbb{W} \mathbb{L}_z - 2\text{sym}(\mathbb{C}^T \mathbb{L}_\eta^{-1} \mathbb{L}_z)$. Recalling the definition of \mathbb{W} , we find

$$\beta_{N,M}^2 = \inf_{\mathbf{z} \in \mathbb{R}^N} \sup_{\boldsymbol{\eta} \in \mathbb{R}^M} \frac{(\mathbf{z}^T \mathbb{L}_z^T \mathbb{W} \mathbb{L}_\eta \boldsymbol{\eta})^2}{(\boldsymbol{\eta}^T \boldsymbol{\eta}) \mathbf{z}^T \mathbb{B} \mathbf{z}} = \inf_{\mathbf{z} \in \mathbb{R}^N} \frac{\mathbf{z}^T \mathbb{L}_z^T \mathbb{W} \mathbb{L}_z \mathbf{z}}{\mathbf{z}^T \mathbb{B} \mathbf{z}}.$$

Introducing the Lagrangian multiplier ν , we can write the optimality conditions as

$$\begin{cases} \mathbb{L}_z^T \mathbb{W} \mathbb{L}_z \mathbf{z} = \nu \mathbb{B} \mathbf{z}; \\ \mathbf{z}^T \mathbb{B} \mathbf{z} = 1. \end{cases}$$

This follows.

The proof of (21) exploits Remark 2.1, and the same argument used to prove (20). We omit the details. \square

2.6 SGreedy+approximation algorithm for the selection of the observation centers

Algorithm 1 summarizes the Greedy procedure for the selection of the transducers' locations $x_1^{\text{obs}}, \dots, x_M^{\text{obs}}$. During the first (stability) stage, we maximize the constant $\beta_{N,M}$ in a Greedy manner. During the second (approximation) stage, we minimize the fill distance $h_M := \sup_{x \in \Omega} \min_{m=1, \dots, M} \|x - x_m^{\text{obs}}\|_2$ in a Greedy manner. We switch from the first to the second stage when the inf-sup constant $\beta_{N,M}$ is larger than an user-defined constant tol : if $\text{tol} = 0$, all the centers are selected through the approximation loop, if $\text{tol} = 1$, all centers are selected through the stability loop. Representative values for tol used in the numerical simulations are $\text{tol} \in [0.2, 0.6]$.

The Greedy procedure was first presented in [9, Algorithm 3.2.1] for the variational update space. We observe that the stability loop — for variational update — corresponds² to the SGreedy algorithm proposed in [1]; on the other hand, the strategy for the approximation step is strongly related to the so-called *farthest-first traversal* approach to the minimax facility location problem (see, e.g, [17]), first proposed by Rosenkrantz et al. in [18]. For the variational update, since $\beta_{N,M}$ is a non-decreasing function of M for a fixed value of N (see [1]), the stability constant remains above the threshold during the approximation stage. On the other hand, for the user-defined update, there is in general no guarantee that the inf-sup constant will be above the threshold at the end of the Greedy procedure since the inner product $((\cdot, \cdot))$ and the induced norm vary with m . In the numerical experiments we investigate the behavior of the inf-sup constant for large values of M .

² In the SGreedy procedure listed in [1, Algorithm 2], steps 6 and 7 of Algorithm 1 are replaced by $\ell_{m+1}^o = \arg \min_{\ell \in \mathcal{L}} |\ell(z_{\min, m} - \mathcal{I}_M(z_{\min, m}))|$, and $\mathcal{U}_{m+1} = \mathcal{U}_m \cup \text{span}\{R_{\mathcal{X}} \ell_{m+1}^o\}$, where $\mathcal{L} = \{\ell(\cdot, x, r_w) : x \in \bar{\Omega}\}$ is the dictionary of available functionals. The approach presented here is easier to implement, and less computationally expensive. Furthermore, the two procedures are asymptotically equivalent for $r_w \rightarrow 0^+$, and return similar results if r_w is small enough compared to the characteristic length-scale of the elements in \mathcal{Z}_N .

Algorithm 1 Greedy stability-approximation balancing (SGreedy+approx) algorithm

Input	$\mathcal{Z}_N = \text{span}\{\zeta_n\}_{n=1}^N$	background space
	M	number of sensors
	$tol > 0$	threshold for the stability constant
	$\phi : \Omega \times \Omega \rightarrow \mathbb{R}$	update generator
Output	\mathcal{U}_M	update space

Stability

- 1: Compute $x_1^{\text{obs}} := \arg \max_{x \in \bar{\Omega}} |\zeta_1(x)|$, $\mathcal{U}_1 = \text{span}\{\phi(\cdot, x_1^{\text{obs}})\}$, $m = 1$
- 2: **while** $m \leq M$ **do**
- 3: Compute $\beta_{N,m} = \min_{w \in \mathcal{Z}_N} \max_{v \in \mathcal{U}_m} \frac{((w,v))}{\|w\| \|v\|}$.
- 4: **if** $\beta_{N,m} \leq tol$ **then**
- 5: Compute $z_{\min,m} := \arg \min_{z \in \mathcal{Z}_N} \max_{v \in \mathcal{U}_m} \frac{((z,v))}{\|z\| \|v\|}$.
- 6: Compute $x_{m+1}^{\text{obs}} := \arg \max_{x \in \bar{\Omega}} |z_{\min,m}(x) - \mathcal{I}_m(z_{\min,m})(x)|$.
- 7: Set $\mathcal{U}_{m+1} = \mathcal{U}_m \cup \text{span}\{\phi(\cdot, x_{m+1}^{\text{obs}})\}$, $m = m + 1$.
- 8: **else**
- 9: **Break**
- 10: **end if**
- 11: **end while**

Approximation

- 1: **while** $m \leq M$ **do**
 - 2: Compute $x_{m+1}^{\text{obs}} := \arg \max_{x \in \bar{\Omega}} \min_{m'=1, \dots, m} \|x - x_{m'}^{\text{obs}}\|_2$.
 - 3: Set $\mathcal{U}_{m+1} = \mathcal{U}_m \cup \text{span}\{\phi(\cdot, x_{m+1}^{\text{obs}})\}$, $m = m + 1$.
 - 4: **end while**
-

2.7 Choice of ξ

The choice of ξ is performed using holdout validation. We consider two mutually exclusive datasets $\mathcal{D}_M^{\text{train}} = \{(\ell_m^o, y_m)\}_{m=1}^M$ and $\mathcal{D}_I^{\text{val}} = \{(\ell_i^o, y_i)\}_{i=1}^I$; given the finite-dimensional search space $\Xi \subset \mathbb{R}_+$, we then select ξ^* such that

$$\xi^* = \arg \min_{\xi \in \Xi} \widehat{\text{MSE}}(I) := \frac{1}{I} \sum_{i=1}^I (y_i - \ell_i^o(u_\xi^*))^2,$$

where u_ξ^* is the PBDW solution based on the training dataset $\mathcal{D}_M^{\text{train}}$, for $\xi = \bar{\xi}$.

In this work, we consider validation measurements of the form $\{y_i = \ell(u, x_i^{\text{obs}}, r_w) + \epsilon_i\}_{i=1}^I$, where ℓ is introduced in (8), and $x_1^{\text{obs}}, \dots, x_I^{\text{obs}}$ are independent realizations of an uniformly-distributed random variable over Ω , $X \sim \text{Uniform}(\Omega)$. If r_w is small, for this choice of the observation centers, and assuming that $\epsilon_1, \dots, \epsilon_I$ are independent realizations of $\epsilon \sim (0, \sigma^2)$, it is possible to show that (see [8])

$$\mathbb{E} [\widehat{\text{MSE}}(I)] = \frac{1}{|\Omega|} \|u^{\text{true}} - u_\xi^*\|_{L^2(\Omega)}^2 + \sigma^2 + C(r_w, u^{\text{true}} - u_\xi^*),$$

where $C(r_w, u^{\text{true}} - u_\xi^*) \rightarrow 0$ as $r_w \rightarrow 0^+$ if $\nabla(u^{\text{true}} - u_\xi^*) \in L^q(\Omega)$, $q > d$. Therefore, for sufficiently large values of I , the validation procedure approximately minimizes the L^2 error.

The choice of the number of validation measurements is a trade-off between experimental cost (given by the number of transducers dedicated to validation) and reliability of the validation procedure. κ -fold cross-validation (see, e.g., [19, Chapter 7] and [20]) reduces the experimental cost by partitioning the training dataset \mathcal{D}_M into κ equal-sized subsamples (folds) $\{\mathcal{D}_M^{(k)}\}_{k=1}^\kappa$. Of the κ folds, a single fold is retained for testing and the remaining $\kappa - 1$ folds are used for training. The procedure is then repeated κ times with each of the κ folds used once as the validation dataset. After having selected the hyper-parameter ξ , the entire dataset is finally used for training. We emphasize that cross-validation relies on the assumption that the pairs (x_m^{obs}, y_m) are independently sampled from the joint distribution of inputs and outputs (*random design*). On the other hand, in our framework the training centers $\{x_m^{\text{obs}}\}_{m=1}^M$ are chosen deterministically (*fixed design*). For this reason, in this work, we simply consider holdout validation with $I = M/2$; we refer to a future work for more advanced cross-validation strategies.

2.8 Extension to vector-valued problems

We can trivially extend the Greedy procedure for the selection of the observation centers to vector-valued fields $u^{\text{true}} = [u_1^{\text{true}}, \dots, u_J^{\text{true}}] \in \mathcal{X} = \mathcal{X}(\Omega; \mathbb{R}^J)$. Assuming that each transducer is able to measure all J components of the true field in all d directions, at each iteration of the Greedy algorithm, we select x_m^{obs} such that (compare with Algorithm 1, step 6)

$$x_{m+1}^{\text{obs}} = \arg \max_{x \in \Omega} \|z_{\min}(x) - \mathcal{I}_m(z_{\min})(x)\|_2.$$

Then, we add J modes $\phi_1(\cdot, x_{m+1}^{\text{obs}}), \dots, \phi_J(\cdot, x_{m+1}^{\text{obs}}) \in \mathcal{X}$ in the update; note that the subspace \mathcal{U}_m is $m \times J$ dimensional).

As regards the choice of the J generators, we might consider the generator

$$\phi_i(\cdot, x) = R_{\mathcal{X}} \ell_i(\cdot, x, R_w), \quad \text{where } \ell_i(u, x, R_w) = \ell(u_i, x, R_w), \quad i = 1, \dots, J; \quad (22a)$$

and $R_w \geq r_w$. Alternatively, we might consider the update

$$\phi_i(\cdot, x) = \Phi(\|\cdot - x\|_2) \mathbf{e}_i, \quad i = 1, \dots, J; \quad (22b)$$

where Φ is a properly-defined kernel, and $\mathbf{e}_1, \dots, \mathbf{e}_J$ are the canonical vectors in \mathbb{R}^J .

Note that, in the case of incompressible flows considered in section 5, for a proper choice of the ambient space \mathcal{X} , the update space (22a) is divergence-free, while the user-defined update space (22b) is not divergence-free. For this reason, we might resort to matrix-valued divergence-free kernels (see, e.g., [21]). We refer to a future work for the use of matrix-valued divergence-free kernels in the PBDW framework.

3 Error analysis

We present an error analysis for general linear functionals in the presence of noise, based on the identification of two sources: the first source is related to the finite number of measurements, while the second source is related to the presence of noise. For simplicity of notation, we consider scalar problems; however, the analysis can be trivially extended to vector-valued fields. Given the measurements $\{y_m = \ell_m^o(u^{\text{true}}) + \epsilon_m\}_{m=1}^M$, we define the vector $\mathbf{u}^{\text{opt}} = [\tilde{\boldsymbol{\eta}}^{\text{opt}}, \mathbf{z}^{\text{opt}}] \in \mathbb{R}^{M+N}$ corresponding to the solution $u_{\xi=0}^{\text{opt}}$ to (6) fed with perfect observations $\{y_m^{\text{true}} = \ell_m^o(u^{\text{true}})\}_{m=1}^M$ (see (19)). On the other hand, we define $\mathbf{u}_{\xi}^* = [\tilde{\boldsymbol{\eta}}_{\xi}^*, \mathbf{z}_{\xi}^*]$ corresponding to the solution u_{ξ}^* to the stabilized formulation (5), fed with imperfect observations.

We first present the result for perfect measurements.

Proposition 3.1. *Let $y_m = \ell_m^o(u^{\text{true}})$, $m = 1, \dots, M$, let $\beta_{N,M} > 0$, and let \mathcal{U}_M satisfy (7). We denote by $u_{\xi=0}^{\text{opt}}$ the solution to the PBDW formulation (6). Then, the following estimates hold:*

$$\left\| u^{\text{true}} - u_{\xi=0}^{\text{opt}} \right\| \leq \frac{1}{\beta_{N,M}} \inf_{z \in \mathcal{Z}_N} \inf_{q \in \mathcal{U}_M \cap \mathcal{Z}_N^{\perp, \|\cdot\|}} \left\| u^{\text{true}} - z - q \right\|; \quad (23a)$$

$$\left\| u^{\text{true}} - u_{\xi=0}^{\text{opt}} \right\| \leq \frac{\sqrt{4 + 6\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}^2}}{\beta_{N,M}} \inf_{z \in \mathcal{Z}_N} \inf_{q \in \mathcal{U}_M \cap \mathcal{Z}_N^{\perp, \|\cdot\|}} \left\| u^{\text{true}} - z - q \right\|. \quad (23b)$$

Proof. Thanks to the variational interpretation of the user-defined update (see Proposition 2.1), proof of (23a) follows directly from [22, Remark 2.12]. On the other hand, exploiting (23a) and (13), we find

$$\begin{aligned} \left\| u^{\text{true}} - u_{\xi=0}^{\text{opt}} \right\| &\leq \sqrt{2} \left\| u^{\text{true}} - u_{\xi=0}^{\text{opt}} \right\| \leq \frac{\sqrt{2}}{\beta_{N,M}} \inf_{z \in \mathcal{Z}_N} \inf_{q \in \mathcal{U}_M \cap \mathcal{Z}_N^{\perp, \|\cdot\|}} \left\| u^{\text{true}} - z - q \right\| \\ &\leq \frac{\sqrt{4 + 6\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}^2}}{\beta_{N,M}} \inf_{z \in \mathcal{Z}_N} \inf_{q \in \mathcal{U}_M \cap \mathcal{Z}_N^{\perp, \|\cdot\|}} \left\| u^{\text{true}} - z - q \right\|, \end{aligned}$$

which proves (23b). \square

If we introduce the matrices and vectors

$$\mathbb{A}(\xi) = \begin{bmatrix} (\xi M \mathbb{I} + \mathbb{L}_{\eta} \mathbb{L}_{\eta}^T) & \mathbb{L}_z \\ \mathbb{L}_z^T & 0 \end{bmatrix}; \quad \mathbf{e} = \begin{bmatrix} \boldsymbol{\epsilon} \\ \mathbf{0} \end{bmatrix}; \quad \boldsymbol{\epsilon} = [\epsilon_1, \dots, \epsilon_M]^T;$$

we obtain the following identity that links \mathbf{u}_{ξ}^* to \mathbf{u}^{opt}

$$\mathbb{A}(\xi) \mathbf{u}_{\xi}^* = \mathbb{A}(0) \mathbf{u}^{\text{opt}} + \mathbf{e} = \mathbb{A}(\xi) \mathbf{u}^{\text{opt}} - \xi M \begin{bmatrix} \tilde{\boldsymbol{\eta}}^{\text{opt}} \\ \mathbf{0} \end{bmatrix} + \mathbf{e}. \quad (24)$$

Identity (24) can be used to estimate the bias of our estimate, and the expected error. For simplicity, we present below estimates for the errors in the coefficients, $\mathbf{u}_{\xi}^* - \mathbf{u}^{\text{opt}}$; the estimates can also be extended to compute the state estimation error in an integral norm of interest. We omit the details.

Proposition 3.2. *Suppose that $\epsilon_1, \dots, \epsilon_M$ are independent realizations of $\epsilon \sim (0, \sigma^2)$. Then, the following hold:*

$$\|\mathbb{E}[\mathbf{u}_\xi^*] - \mathbf{u}^{\text{opt}}\|_2 \leq \frac{\xi M}{s_{\min}(\mathbb{A}(\xi))} \|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2; \quad (25)$$

and

$$\mathbb{E} [\|\mathbf{u}_\xi^* - \mathbf{u}^{\text{opt}}\|_2^2] \leq \left(\frac{\xi M}{s_{\min}(\mathbb{A}(\xi))} \|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2 \right)^2 + \sigma^2 \text{trace} (\mathbb{A}(\xi)^{-1} \Sigma \mathbb{A}(\xi)^{-T}); \quad (26)$$

where $s_{\min}(\mathbb{A}(\xi))$ denotes the minimum singular value of $\mathbb{A}(\xi)$, $\Sigma = \begin{bmatrix} \mathbb{I} & 0 \\ 0 & 0 \end{bmatrix}$.

Proof. Exploiting (24), we find

$$\mathbb{A}(\xi) \mathbf{u}_\xi^* = \mathbb{A}(\xi) \mathbf{u}^{\text{opt}} - \xi M \begin{bmatrix} \tilde{\boldsymbol{\eta}}^{\text{opt}} \\ \mathbf{0} \end{bmatrix} + \mathbf{e} \Rightarrow \|\mathbb{E}[\mathbf{u}_\xi^*] - \mathbf{u}^{\text{opt}}\|_2 \leq \frac{\xi M}{s_{\min}(\mathbb{A}(\xi))} \|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2;$$

which is (25).

In order to show (26), we first observe that (cf. [23, Thm. C, Chapter 14.4]):

$$\mathbb{E} [\|\mathbb{E}[\mathbf{u}_\xi^*] - \mathbf{u}^{\text{opt}}\|_2^2] = \sigma^2 \text{trace} (\mathbb{A}(\xi)^{-1} \Sigma \mathbb{A}(\xi)^{-T}).$$

Then, we find

$$\begin{aligned} \mathbb{E} \|\mathbf{u}_\xi^* - \mathbf{u}^{\text{opt}}\|_2^2 &= \|\mathbb{E}[\mathbf{u}_\xi^*] - \mathbf{u}^{\text{opt}}\|_2^2 + \mathbb{E} [\|\mathbb{E}[\mathbf{u}_\xi^*] - \mathbf{u}_\xi^*\|_2^2] \\ &\leq \left(\frac{\xi M}{s_{\min}(\mathbb{A}(\xi))} \|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2 \right)^2 + \sigma^2 \text{trace} (\mathbb{A}(\xi)^{-1} \Sigma \mathbb{A}(\xi)^{-1}), \end{aligned}$$

which is (26). \square

We observe that the bound for the mean squared error (26) is the sum of two contributions: the former $-\frac{\xi M}{s_{\min}(\mathbb{A}(\xi))} \|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2$ involves the accuracy of the background space, measured by $\|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2$, and is monotonically increasing with ξ ; the latter $-\sigma^2 \text{trace} (\mathbb{A}(\xi)^{-1} \Sigma \mathbb{A}(\xi)^{-T})$ involves the accuracy of the measurements, and is monotonically decreasing with ξ according to our numerical experience. Therefore, the optimal value of ξ depends on the ratio between “measurement inaccuracy” and “model inaccuracy” $\frac{\sigma}{\|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2}$: if $u^{\text{true}} \in \mathcal{Z}_N$, estimate (26) suggests to pick $\xi \rightarrow \infty$; if $\sigma = 0$, estimate (26) suggests to pick $\xi \rightarrow 0^+$. Since in practice estimates of the ratio $\frac{\sigma}{\|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2}$ are rarely available, our analysis suggests that the value of ξ should be chosen adaptively using (cross-)validation techniques such as the one discussed in section 2.7. These observations are in agreement with [2, Remark 3.3].

Remark 3.1. (extension to complex-valued problems) *Proposition 3.2 can be trivially extended to the complex-valued case. Assuming that measurements are of the form*

$$y_m = \ell_m^o(u^{\text{true}}) + \sigma_{\text{re}} \epsilon_m^{\text{re}} + i \sigma_{\text{im}} \epsilon_m^{\text{im}}, \quad \epsilon_m^{\text{re}}, \epsilon_m^{\text{im}} \stackrel{\text{i.i.d.}}{\sim} (0, 1), \quad \sigma_{\text{re}}, \sigma_{\text{im}} > 0,$$

we find the same estimate for the bias (25), and we find

$$\begin{aligned} \mathbb{E}[\|\mathbf{u}_\xi^\star - \mathbf{u}^{\text{opt}}\|_2^2] &\leq \left(\frac{\xi M}{s_{\min}(\tilde{\mathbf{A}}(\xi))} \|\tilde{\boldsymbol{\eta}}^{\text{opt}}\|_2 \right)^2 + \sigma_{\text{re}}^2 \text{trace} \left(\tilde{\mathbf{A}}(\xi)^{-1} \Sigma^{\text{re}} \tilde{\mathbf{A}}(\xi)^{-T} \right) \\ &\quad + \sigma_{\text{im}}^2 \text{trace} \left(\tilde{\mathbf{A}}(\xi)^{-1} \Sigma^{\text{im}} \tilde{\mathbf{A}}(\xi)^{-T} \right); \end{aligned} \quad (27)$$

where $\tilde{\mathbf{A}}(\xi) = \begin{bmatrix} \text{Re}[\mathbf{A}(\xi)] & -\text{Im}[\mathbf{A}(\xi)] \\ \text{Im}[\mathbf{A}(\xi)] & \text{Re}[\mathbf{A}(\xi)] \end{bmatrix}$, $\Sigma^{\text{re}} = \begin{bmatrix} \Sigma & 0 \\ 0 & 0 \end{bmatrix}$, $\Sigma^{\text{im}} = \begin{bmatrix} 0 & 0 \\ 0 & \Sigma \end{bmatrix}$.

4 Application to Acoustics

We illustrate the behavior of the PBDW formulation presented in this paper through the vehicle of two acoustic Helmholtz problems. Since the objective of this work is to propose user-defined update spaces that improve convergence with respect to the number of observations (M -convergence), we do not study the effect of the primary approximation provided by the background \mathcal{Z}_N : we refer to the PBDW literature for further results concerning the effect of the primary approximation.

4.1 A two-dimensional model problem

The model problem is the same considered in [1, Section 3], and [2, Section 5].

4.1.1 Problem definition

Given the domain $\Omega = (0, 1)^2$, we define the acoustic model problem:

$$\begin{cases} -(1 + i\epsilon\mu) \Delta u_g(\mu) - \mu^2 u_g(\mu) = \mu (2x_1^2 + e^{x_2}) + \mu g & \text{in } \Omega, \\ \partial_n u_g(\mu) = 0 & \text{on } \partial\Omega, \end{cases} \quad (28)$$

where i is the imaginary unit, $\mu > 0$ is the wave number, $\epsilon = 10^{-2}$ is a fixed dissipation, and $g \in L^2(\Omega)$ is a bias term that will be specified later. Here, the parameter $\mu > 0$ constitutes the anticipated, parametric uncertainty in the system, which might model our uncertainty in the speed of sound, while the function g constitutes the unanticipated (non-parametric) uncertainty in the system.

To assess the performance of the PBDW formulation for various configurations, we define the true field u^{true} as the solution to (28) for some $\mu^{\text{true}} \in \mathcal{P}^{\text{bk}}$ and for the following choice of the *bias* g

$$g := 0.5(e^{-x_1} + 1.3 \cos(1.3\pi x_2)). \quad (29a)$$

On the other hand, we define the bk manifold as

$$\mathcal{M}^{\text{bk}} := \{u_{g=0}(\mu) : \mu \in \mathcal{P}^{\text{bk}}\}. \quad (29b)$$

To measure performance, we introduce the relative L^2 and H^1 errors averaged over $|\mathcal{P}_{\text{test}}^{\text{bk}}| = n_{\text{test}}$ fields associated with different choices of the parameter

μ :

$$E_{\text{avg}}^{\text{rel}}(n_{\text{test}}) := \frac{1}{n_{\text{test}}} \sum_{\mu \in \mathcal{P}_{\text{test}}^{\text{bk}}} \frac{\|u^{\text{true}}(\mu) - u_{\xi}^*(\mu)\|_{\star}}{\|u^{\text{true}}(\mu)\|_{\star}}; \quad \|\cdot\|_{\star} = \|\cdot\|_{L^2(\Omega)} \text{ or } \|\cdot\|_{H^1(\Omega)}. \quad (30)$$

In all our tests, we consider $n_{\text{test}} = 10$ equispaced parameters in \mathcal{P}^{bk} .

We model the (synthetic) observations by a Gaussian convolution with standard deviation r_w :

$$\ell_m^o(v) = \text{Gauss}(v, x_m^{\text{obs}}; r_w) = C(x_m^{\text{obs}}) \int_{\Omega} e^{-\frac{1}{2r_w^2} \|x - x_m^{\text{obs}}\|^2} v(x) dx, \quad m = 1, \dots, M; \quad (31a)$$

where $C(x_m^{\text{obs}})$ is a normalization constant such that $\ell_m^o(1) = 1$, and x_m^{obs} denotes the transducer location. In order to simulate noisy measurements, we corrupt the synthetic measurements with homoscedastic random noise:

$$y_{\ell} = \ell_m^o(u^{\text{true}}) + \sigma^{\text{re}} \epsilon_{\ell}^{\text{re}} + i \sigma^{\text{im}} \epsilon_{\ell}^{\text{im}}, \quad \epsilon_{\ell}^{\text{re}}, \epsilon_{\ell}^{\text{im}} \stackrel{\text{iid}}{\sim} \mathcal{N}(0, 1); \quad (31b)$$

where

$$\sigma^{\text{re}} = \text{SNR} \times \text{std}(\{\text{Re}[\ell_m^o(u^{\text{true}})]\}_{m=1}^M), \quad \sigma^{\text{im}} = \text{SNR} \times \text{std}(\{\text{Im}[\ell_m^o(u^{\text{true}})]\}_{m=1}^M), \quad (31c)$$

and SNR denotes the signal-to-noise ratio in the measurements.

4.1.2 PBDW spaces

We introduce the ambient space $\mathcal{X} = H^1(\Omega)$ endowed with the inner product:

$$(u, v) = \int_{\Omega} u \bar{v} + \nabla u \cdot \nabla \bar{v} dx. \quad (32)$$

Note that $\bar{(\cdot)}$ denotes the complex conjugate of (\cdot) . The background space \mathcal{Z}_N is built using the Weak-Greedy algorithm (see, e.g., [24]): we refer to [1] for further details.

As regards the update space, we consider the variational update associated with the inner product (32), and the user-defined updates $\mathcal{U}_M = \text{span}\{\phi(\lambda \|\cdot - x_m^{\text{obs}}\|_2)\}_{m=1}^M$ for

$$\begin{cases} \phi(r) = \frac{1}{(1+r^2)^2} & \text{inverse multiquadrics;} \\ \phi(r) = (1-r)_+^4 (4r+1) & \text{csRBF.} \end{cases}$$

The observation centers $\{x_m^{\text{obs}}\}_{m=1}^M$ are chosen according to Algorithm 1. As regards the choice of the kernel scale, we here set $\lambda = 1$ for inverse multiquadrics, and $\lambda = 2$ for csRBF. We remark that the optimal value for the kernel scale parameter λ strongly depends on the number of measurements, and also on the characteristic length-scale of the field $u^{\text{true}} - z_{\xi}^*$; therefore, adaptation of the parameter λ might improve performance, particularly for large values of M .

4.1.3 Numerical results

In Figures 1(a)-(b)-(c), we show the behavior of the inf-sup constant $\beta_{N,M}$ with M for the three different choices of the update space (and thus for the three choices of the norm $\|\cdot\|$), $r_w = 0.01$ and $N = 6$, and for centers $\{x_m^{\text{obs}}\}_{m=1}^M$ selected by the SGreedy algorithm with $\text{tol} = 0.6$; to measure performance, we compare the results with the ones obtained using randomly-generated centers. For the second choice, we average over 35 different random choices of the M centers. We observe that the SGreedy selection of the sensor locations leads to a more stable formulation compared to randomly-generated points. In Figures 1(d)-(e)-(f), we show the centers $\{x_m^{\text{obs}}\}_{m=1}^M$ selected by the SGreedy algorithm for the three different choices of the update space: for all the three choices of the update space the Greedy procedure selects most points along the principal diagonal $(0, 0) \rightarrow (1, 1)$.

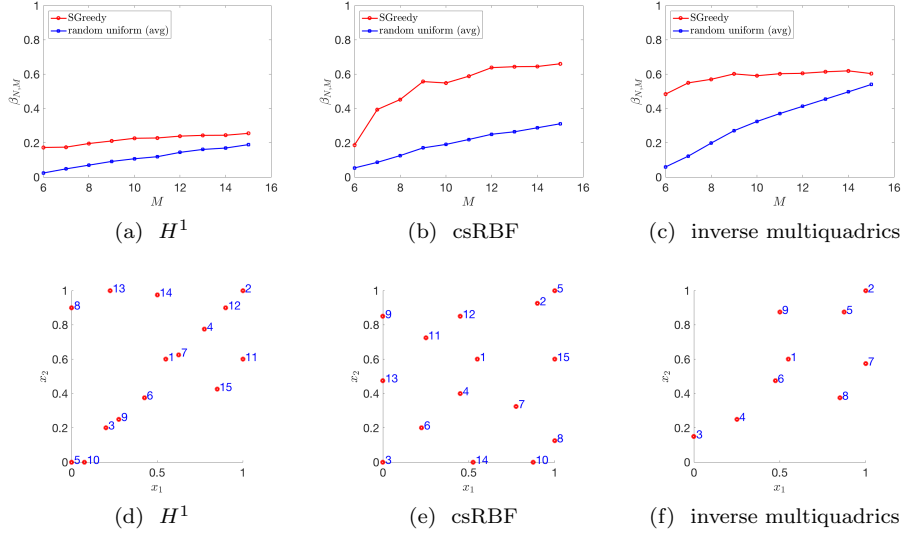


Figure 1: Application to a two-dimensional acoustic problem: application of the SGreedy algorithm ($N = 6$, $r_w = 0.01$, $\text{tol} = 0.6$). Results for random centers are averaged over 35 random trials.

In Figure 2, we show the behavior of $\beta_{N=6,M}$ for three choices of the update space considered, for $M = 6, \dots, 150$. We observe that, for the user-defined update, $\beta_{N,M}$ is not monotonic increasing with M . Nevertheless, we do not observe pathologic behaviors of the inf-sup constant as M increases.

In Figure 3, we show the behavior of the Lebesgue constant $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ defined in (13), for the three choices of the update. As expected for the variational update space, the Lebesgue constant is equal to one. We also observe that $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ is significantly larger for inverse multiquadrics than for csRBF: recalling estimate (23b), the use of inverse multiquadrics (and more in general of smooth kernels) is appropriate only for smooth fields.

Figure 4 shows the behavior of the relative error $E_{\text{avg}}^{\text{rel}}$ (30) with M for perfect observations, $N = 6$, and two values of r_w in (31). We observe that the user-defined update based on inverse multiquadrics leads to more accurate state

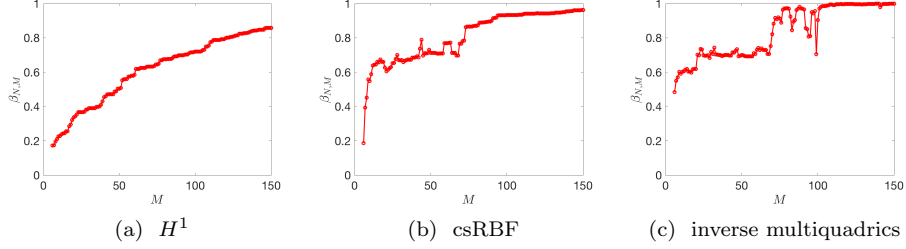


Figure 2: Application to a two-dimensional acoustic problem: behavior of $\beta_{N,M}$ for $M = 6, \dots, 150$, for three choices of the update ($N = 6$, $r_w = 0.01$, $tol = 0.6$).

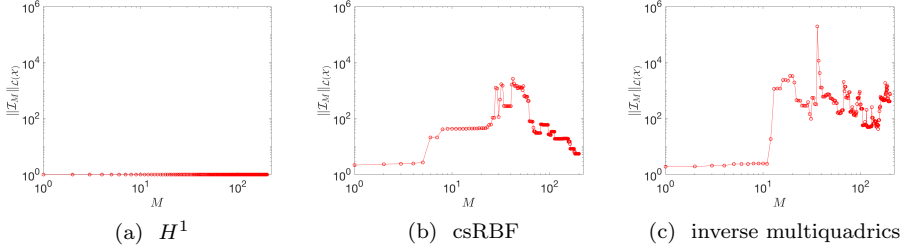


Figure 3: Application to a two-dimensional acoustic problem: behavior of $\|\mathcal{I}_M\|_{\mathcal{L}(\mathcal{X})}$ ($N = 6$, $r_w = 0.01$, $tol = 0.6$).

estimates compared to the standard H^1 PBDW, particularly for $r_w = 0.01$. We further observe that inverse multiquadrics outperform csRBF in all tests considered: since the true state is smooth in Ω , the inverse multiquadric kernel — which is C^∞ — exhibits superior approximation properties compared to the C^2 csRBF kernel (see [7, Chapter 11]).

Figure 5 shows results for the behavior of the L^2 relative error $E_{\text{avg}}^{\text{rel}}$ with M for imperfect observations for the user-defined (inverse multiquadrics) update and for the variational H^1 update. The error $E_{\text{avg}}^{\text{rel}}$ is averaged over 25 realizations of the homoscedastic random noise. More in detail, we here consider three different noise levels SNR; we set $N = 4$, and we consider $r_w = 0.01$ in (31). Furthermore, in order to select the value of ξ , we resort to the hold-out validation procedure outlined in section 2.7 based on additional $I = M/2$ measurements, associated with uniformly-generated points in Ω . The rate of convergence with M seems to weakly depend on the choice of the update; nevertheless, also for noisy measurements, the use of inverse multiquadrics strongly improves performance.

In Figure 6 we discuss the interpretation of the regularization parameter ξ . Towards this end, we show the behavior of the mean squared error $\widehat{\text{MSE}}(I)$ introduced in section 2.7 for two different choices of the true field ($u^{\text{true}} = u_g(\mu = 5.8)$ and $u^{\text{true}} = u_{g=0}(\mu = 5.8)$), two different noise levels, and $N = 5$, $M = 100$, $I = 50$. Note that for $g = 0$ u^{true} belongs to the bk manifold. We observe that the optimal value of ξ increases as the noise increases, and decreases as the best-fit error increases: this is in good agreement with the discussion in

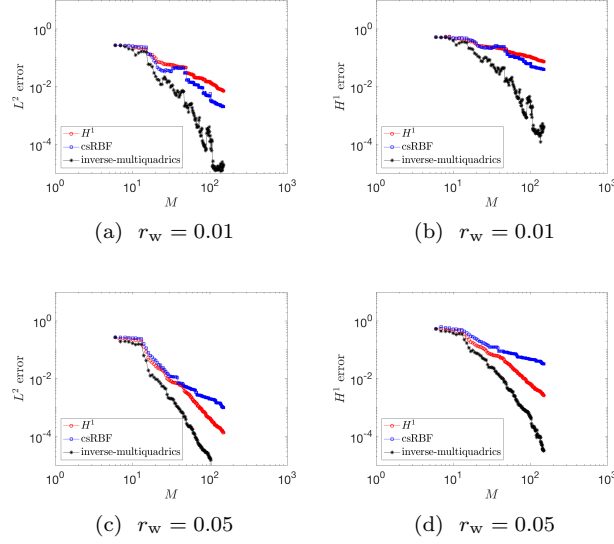


Figure 4: Application to a two-dimensional acoustic problem: M convergence for three different choices of the update space for perfect observations ($N = 6$, $\text{SNR} = 0$, $\text{tol} = 0.6$).

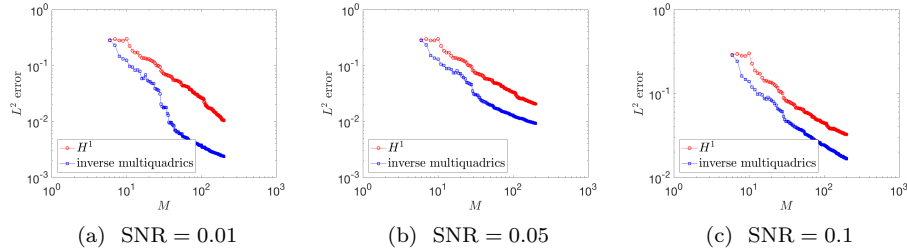


Figure 5: Application to a two-dimensional acoustic problem: M convergence for three different choices of the update space for noisy observations ($N = 4$, $r_w = 0.01$, $\text{tol} = 0.6$). Results are averaged over 25 realizations of the random disturbances for each value of M .

section 3, and also with the results in [2, Figure 4] for pointwise measurements. We further observe that, as anticipated in section 2.7, the error estimator is in good qualitative agreement with the true error $\|u^{\text{true}} - u_{\xi}^*\|_{L^2(\Omega)}^2$: therefore, it can be used to select the optimal value of ξ .

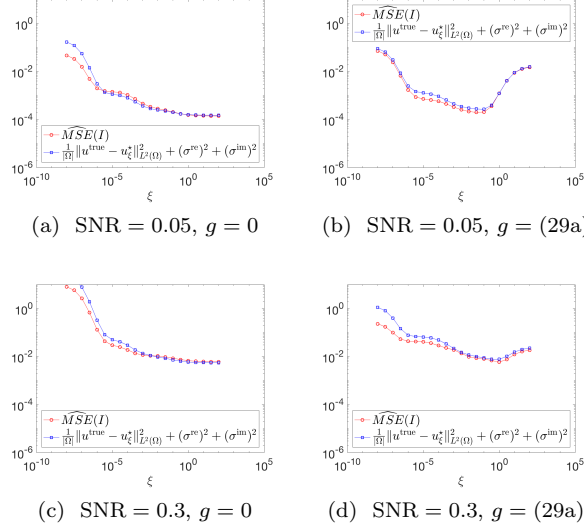


Figure 6: Application to a two-dimensional acoustic problem: interpretation of ξ . Behavior of $\widehat{\text{MSE}}(I)$ and of the error $\frac{1}{|\Omega|} \|u^{\text{true}} - u_{\xi}^{\star}\|_{L^2(\Omega)}^2 + (\sigma^{\text{re}})^2 + (\sigma^{\text{im}})^2$ for two different values of the bias g , and for two different values of SNR. ($M = 100$, $I = 50$, $N = 5$, $r_w = 0.01$, $\text{tol} = 0.3$, empirical update based on inverse multiquadrics).

4.2 A three-dimensional acoustic problem

4.2.1 Problem definition

We consider the three-dimensional model problem:

$$\begin{cases} -(1 + \epsilon i) \Delta u_g(\mu) - (2\pi\mu)^2 u_g(\mu) = g & \text{in } \Omega; \\ \partial_n u_g(\mu) = 0 & \text{on } \partial\Omega; \end{cases} \quad (33)$$

where $\epsilon = 10^{-2}$, $\Omega = (-1.5, 1.5) \times (0, 3) \times (0, 3) \setminus \Omega^{\text{cut}}$, $\Omega^{\text{cut}} = (-0.5, 0.5) \times (0.25, 0.5) \times (0, 1)$. Figure 7 shows the geometry. In this example, we consider the bk manifold $\mathcal{M}^{\text{bk}} = \{u^{\text{bk}}(\mu) = u_{g^{\text{bk}}}(\mu) : \mu \in \mathcal{P}^{\text{bk}} = [0.1, 0.5]\}$, and we define the true field as the solution to (33) for some $\mu^{\text{true}} \in \mathcal{P}^{\text{bk}}$ and $g = g^{\text{true}}$, where

$$g^{\text{bk}}(x) = 10 e^{-\|x - p^{\text{bk}}\|_2^2}; \quad g^{\text{true}}(x) = 10 e^{-\|x - p^{\text{true}}\|_2^2};$$

and $p^{\text{bk}} = [0, 2, 1]$, $p^{\text{true}} = [-0.1, 2, 1]$. Parameterized uncertainty in the system models uncertainty in the input frequency μ ; non-parametric or unanticipated uncertainty is here associated with the incorrect location of the acoustic source ($p^{\text{bk}} \neq p^{\text{true}}$). Computations are based on a P2 FE discretization with roughly $\mathcal{N} = 16000$ degrees of freedom in Ω . Figure 8 shows the bk and true solutions for two values of μ .

As in the previous example, we model the synthetic observations by a Gaussian convolution with standard deviation r_w , see (31). For simplicity, in the tests below, we only consider perfect measurements. Furthermore, we measure

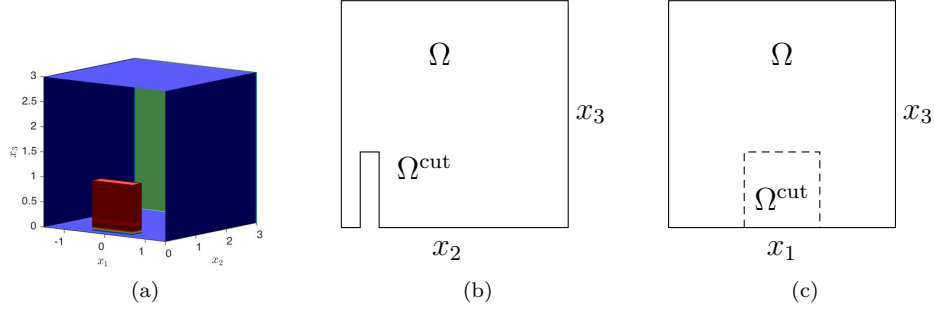


Figure 7: Application to a three-dimensional acoustic problem: computational domain.

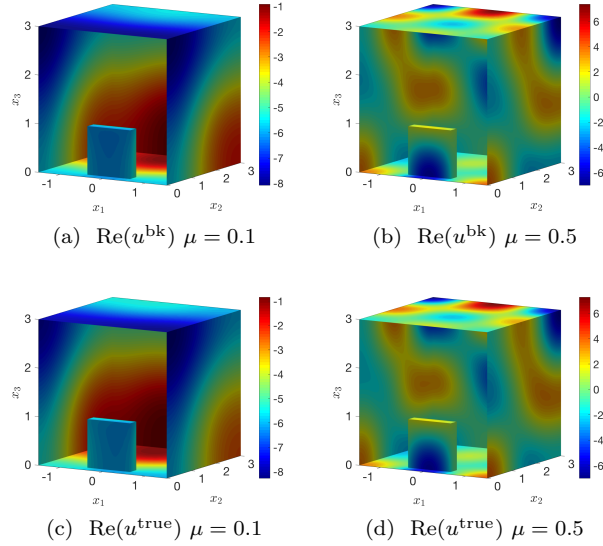


Figure 8: Application to a three-dimensional acoustic problem: visualization of bk and true fields.

performance by computing the relative L^2 and H^1 errors $E_{\text{avg}}^{\text{rel}}$ (30) for $n_{\text{test}} = 10$ different choices of the parameter μ in \mathcal{P}^{bk} .

4.2.2 PBDW spaces

We consider the ambient space $\mathcal{X} = H^1(\Omega)$ endowed with the inner product (\cdot, \cdot) (32). Furthermore, the background space \mathcal{Z}_N is built using the Weak-Greedy algorithm based on the residual.

As regards the update space, we consider the variational update associated with the inner product (32), and the user-defined updates $\mathcal{U}_M = \text{span}\{\phi(\lambda) \cdot -x_m^{\text{obs}}\|_2\}_{m=1}^M$ for $\phi(r) = \frac{1}{1+r^2}$ (inverse multiquadrics) and $\lambda = 1$. The observation centers $\{x_m^{\text{obs}}\}_{m=1}^M$ are chosen according to Algorithm 1.

4.2.3 Numerical results

In Figure 9, we perform the same test of Figure 1. We compare the behavior of the inf-sup constant $\beta_{N=30,M}$ with M using the SGreedy procedure, and using randomly-generated centers. For the second choice, we average over 35 different random choices of the M centers. As in the previous example, the Greedy procedure improves the stability of the PBDW formulation.

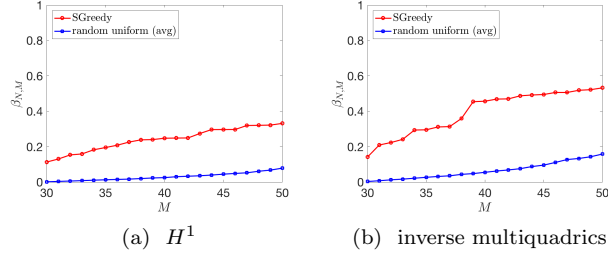


Figure 9: Application to a three-dimensional acoustic problem: application of the SGreedy algorithm ($N = 30$, $r_w = 0.02$, $tol = 0.4$). Results for random centers are averaged over 35 random trials.

Figure 4 shows the behavior of the relative error $E_{\text{avg}}^{\text{rel}}$ (30) with M for perfect observations, $N = 30$, and $r_w = 0.02$ in (31). As in the previous case, the user-defined update based on inverse multiquadrics leads to more accurate state estimates compared to the standard H^1 PBDW.

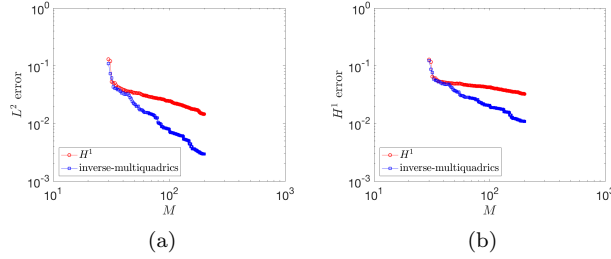


Figure 10: Application to a three-dimensional acoustic problem: M convergence for two different choices of the update space for perfect observations ($N = 30$, $r_w = 0.02$, $tol = 0.4$).

5 Application to Fluid Mechanics

5.1 Problem statement

We consider the following model problem³:

$$\left\{ \begin{array}{ll} -\frac{1}{\text{Re}} \nabla \cdot (\nabla u_g + \nabla u_g^T) + (u_g \cdot \nabla) u_g + \nabla p_g = 0 & \text{in } \Omega \\ \nabla \cdot u_g = 0 & \text{in } \Omega \\ p_g \mathbf{n} - \frac{1}{\text{Re}} (\nabla u_g + \nabla u_g^T) \mathbf{n} = 0 & \text{on } \Gamma_{\text{out},1} \cup \Gamma_{\text{out},2} \\ u_g = g \mathbf{e}_1 & \text{on } \Gamma_{\text{in}} \\ u_g = 0 & \text{on } \partial \Gamma_{\text{hom}} = \Omega \setminus (\Gamma_{\text{in}} \cup \Gamma_{\text{out}}) \end{array} \right. \quad (34)$$

where the domain Ω is depicted in Figure 11(a). We then define the bk and true manifolds as follows:

$$\mathcal{M}^{\text{bk}} = \{u_g(\text{Re}) : \text{Re} \in [50, 350], \ g(x_2) = 4(1 - x_2)x_2\};$$

and

$$\mathcal{M}^{\text{true}} = \{u_g(\text{Re}) : \text{Re} \in [50, 350], \ g(x_2) = 4(1 - x_2)x_2(1 + 0.1 \sin(2\pi x_2))\}.$$

Here, uncertainty in $\mu = \text{Re}$ constitutes the anticipated (parametric) uncertainty in the system, while uncertainty in the inflow condition is the unanticipated (non-parametric) uncertainty.

As in the previous examples, we model synthetic observations by a Gaussian convolution with standard deviation $r_w = 0.01$. Furthermore, we resort to a conforming Taylor-Hood P3-P2 Finite Element discretization with $\mathcal{N}_u = 24038$ degrees of freedom.

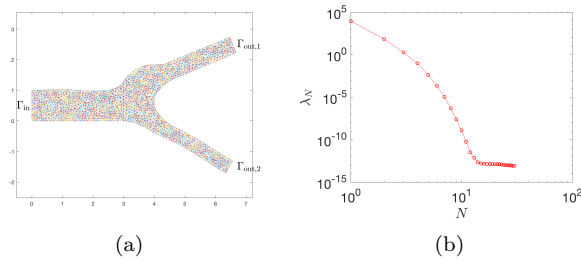


Figure 11: Application to Fluid Dynamics. Figure (a): computational domain; Figure (b): behavior of the POD eigenvalues ($n_{\text{train}} = 100$).

³ The configuration is similar to the one considered in [25, section 5]; however, while here we consider a 2D domain, in [25] the authors consider a more realistic axis-symmetric model.

5.2 PBDW spaces

We consider the ambient space $\mathcal{X} = \{v \in [H_{0,\Gamma_{\text{hom}}}(\Omega)]^2 : \nabla \cdot v = 0\}$ endowed with the inner product:

$$(u, v) = \int_{\Omega} \nabla u : \nabla v + u \cdot v \, dx.$$

The background space is built using Proper Orthogonal Decomposition based on the (\cdot, \cdot) inner product (see, e.g., [26]). Figure 11(b) shows the behavior of the POD eigenvalues. On the other hand, we consider the update generators:

$$\phi_i(\cdot, x) = R_{\mathcal{X}} \ell_i(\cdot, x, R_w), \quad \ell_i(u, x, R_w) = \ell(u_i, x, R_w), \quad i = 1, 2, \quad (35)$$

for several values of $R_w \geq r_w$. We observe that the update space is divergence-free; furthermore, it satisfies the no-slip boundary conditions on Γ_{hom} .

5.3 Numerical results

In Figure 12, we show the performance of the SGreedy procedure for $N = 5$ and $R_w = 0.05$ ($tol = 0.3$). Figure 12(a) shows the behavior of the inf-sup constant $\beta_{N,M}$ with M , for the user-defined update with $R_w = 0.05$: we observe that the SGreedy procedure outperforms on average the random uniform selector. Figure 12(b) shows the location of the points selected by the SGreedy (stabilization stage) Algorithm. We observe that SGreedy selects points in the boundary layer that develops near the junction: this can be explained by recalling that the Reynolds number — the parameter associated with the solution manifold — deeply affects the thickness of the boundary layer.

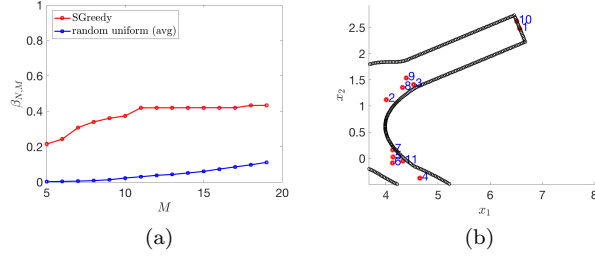


Figure 12: application of the SGreedy + approx algorithm. Figure (a): behavior of the inf-sup constant $\beta_{N,M}$ with M , for the user-defined update with $R_w = 0.05$; Figure (b): centers $\{x_m^{\text{obs}}\}_m$ selected by the SGreedy algorithm ($N = 5$, $r_w = 0.01$, $tol = 0.3$).

Figure 13 shows the behavior of the relative error $E_{\text{avg}}^{\text{rel}}$ (30) with M for perfect measurements, $N = 5$, and three values of R_{width} in (35). We observe that for $R_{\text{width}} = 0.01$ the user-defined update corresponds to the variational update. As for the previous test cases, the use of an user-defined update strongly improves performance, particularly for moderate-to-large values of M .

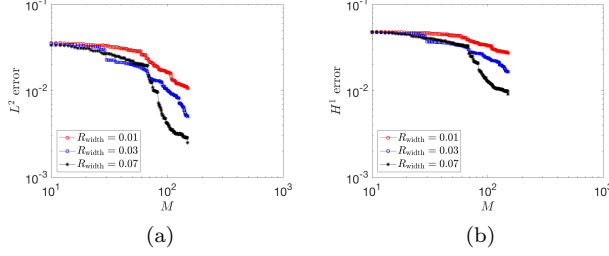


Figure 13: M -convergence. Behavior of the relative averaged error $E_{\text{avg}}^{\text{rel}}$ over $n_{\text{test}} = 10$ different true fields in $\mathcal{M}^{\text{true}}$. ($N = 5$, $r_w = 0.01$, $\text{tol} = 0.3$).

6 Conclusions

In this paper, we presented a number of extensions to the PBDW formulation for state estimation. First, we proposed a Tikhonov regularization of the original PBDW statement for general linear functionals, which relies on holdout validation, to systematically deal with noisy measurements. Second, we proposed user-defined update spaces, which guarantee rapid convergence with respect to the number of measurements M and also might not require the solution to M Riesz problems. Third, we presented an *a priori* error analysis that provides insights into the role of the regularization hyper-parameter ξ associated with the penalized formulation.

We identify a number of future research directions to improve the PBDW formulation and extend its range of applications. First, we wish to extend the formulation to different models for the experimental noise, and also to probabilistic background. Towards this end, we wish to rely on the connection between PBDW and PSM established in [2], and recapped in section 2.2. Second, we wish to extend the formulation to time-dependent problems. This might be accomplished by exploiting a space-time variational formulation ([27]) to incorporate the space-time structure of the evolution equations in the empirical expansion.

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