Modal Analysis of Bulk Current Injection Tests Involving Multiwire Harnesses

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***Abstract*—Modal analysis is a powerful tool for noise identification and predicting noise voltages and currents. For this reason, it can be adopted to infer the outcomes of bulk current injection (BCI) tests on multi-wire bundles for conducted susceptibility verifications through a suitable model of mode conversion. Moreover, upper and lower limits for terminal voltages and currents can be computed through statistical investigations, allowing to identify best- and worst-case scenarios for the considered test campaign. In this framework, a decoupled modal-domain analysis is designed and presented for predicting the results of conducted susceptibility tests involving BCI probes. In particular, this work aims to improve the accuracy of the modal analysis by introducing an intermediate step in the procedure, while ensuring efficiency compared to the traditional method working in the physical domain.**

***Index Terms*—Bulk current injection, conducted susceptibility, epistemic uncertainty, hybrid probabilistic-possibilistic uncertainty quantification, modal analysis, mode conversion**

I. Introduction

Several Electromagnetic compatibility (EMC) military [1] and civil standards [2]–[6] foresee the use of Bulk Current Injection (BCI) probes for conducted susceptibility verifications of electrical products. Moreover, some companies are exploiting BCI test procedures for internal pre-compliance tests. Due to the inclusion of BCI-based methods in conducted susceptibility assessments, pulsed tests [7] and the possibility of formalizing an equivalence between injected conducted noise and interference coupled due to radiated susceptibility [8], several models were developed during the past years. Namely, circuit [9], black-box [10] and electromagnetic models [11] are available in the literature.

In particular, several circuit and electromagnetic representations of BCI test setups were proposed for single wire [12], multi-wire victim bundles [13], and twisted-wire pairs (TWPs) [14]. The behaviour of the system is predicted resorting to multiconductor transmission line (MTL) theory, passive components which take the loading effects of the clamp on the wires into account, and voltage generators which include the inductive coupling between the probe and the victim wires. However, those representations do not allow to clarify the impact of physical quantities (e.g., the geometrical size of the line) on the measured interference. Thus, a two-step procedure based on modal analysis was proposed in [15] and combined with a hybrid possibilistic-probabilistic investigation with the twofold aim of identifying the causes of mode conversion, and predicting best- and worst-case scenarios due to setup uncertainty [16]. Namely, ad-hoc modal transformation matrices were introduced for a generic N-conductor test setup, allowing to obtain one common mode (CM) and $N-1$ differential modes (DMs). CM is recognized to be the dominant mode in the setup, meaning that it is possible to study its behaviour separately from the DMs in absence of DM-to-CM back interaction. This weak coupling assumption allowed to split equivalent circuits for CM and DMs [17]. Additionally, preliminary analyses led to identify the effect of physical quantities on modes, enabling to consider their variability associated with CM and DM quantities. Finally, a statistical analysis was carried out, by simulation of a single CM wire as the first step, whose results were then used to excite the $N-1$ DM circuits.

This CM-to-DM two-step procedure has been proved [16] to be much faster than the traditional MTL solution (reference solution) in the prediction of phase voltages, while loosing a little of accuracy in specific frequency intervals. To reduce mismatches with the reference prediction in these intervals, this work proposes an adapted CM-to-DM procedure in which an additional step is introduced. Namely, a deterministic simu-

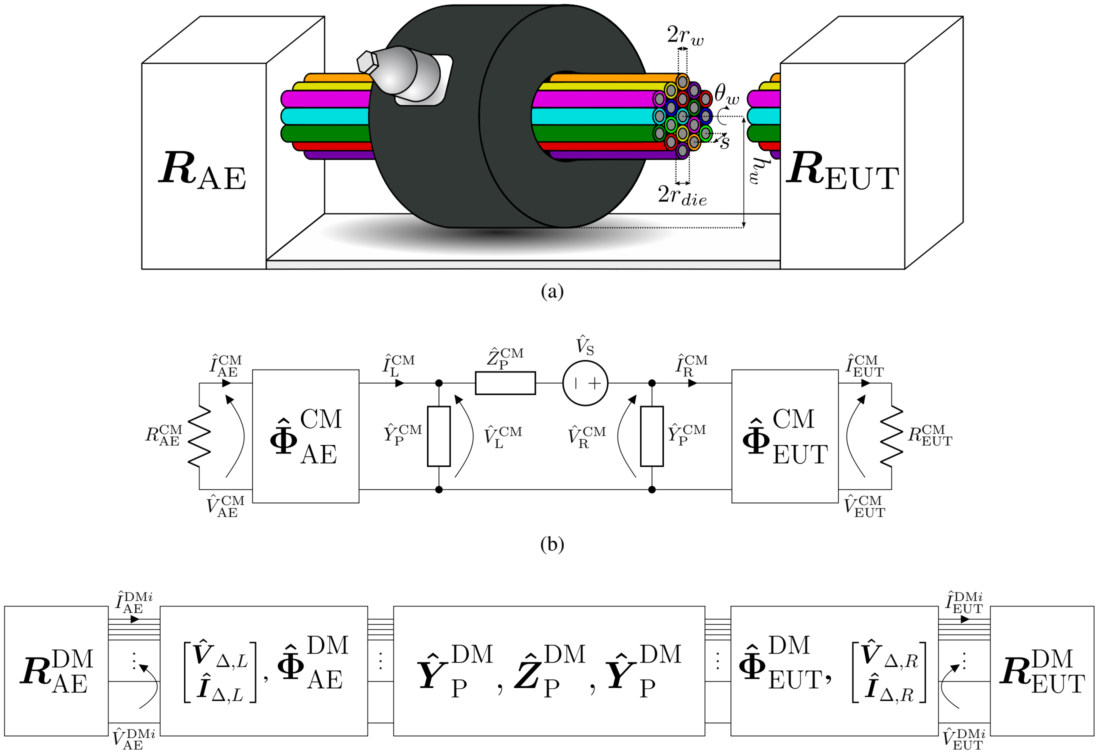

Figure 1. BCI probe clamped on a victim nineteen-conductor MTL (a). The continuity of the line on the equipment under test (EUT) side is interrupted on purpose to allow a clear visualization of the geometrical parameters; (b) and (c) show the corresponding equivalent CM and DMs circuits, respectively. The abbreviation AE stands for auxiliary equipment.

lation of DMs is performed after the CM analysis to have a first estimation of maximum and minimum quantities. Simulation results will prove an appreciable increase in accuracy, at the cost of a slightly slower computational time. However, this approach is still largely outperforming the reference solution in terms of computational time.

The paper is organized as follows. Section II briefly describes the adopted modelling strategy, and introduces the characteristics of the considered test setup. Section III illustrates the main features of the proposed methodology, while Section IV reports an application of this strategy on a 19-conductor setup. Eventually, conclusions are drawn in Section V.

II. Test Setup and Modeling Strategy

The BCI probe modeling technique is based on the deterministic model of BCI probes shown in [13] for multiconductor BCI test setups. Namely, a frequency-dependent impedance matrix $\hat{\boldsymbol{Z}}_{\mathbf{P}}$ as well as a frequency-dependent admittance matrix $\hat{\boldsymbol{Y}}_{\mathbf{P}}$ are introduced in the equivalent circuit to account for the loading effects of the injection device on the victim wires. Moreover, a frequency-dependent equivalent voltage source vector $\hat{\boldsymbol{V}}_{\mathbf{S}}$ is included to represent noise injection into the wires clamped by the probe. In particular, in this work a setup involving a nineteen-wire cable bundle is considered, and an injection probe FCC-F130 A is used for testing (see Fig. 1(a)).

A. Characteristics of the Cable Bundle under Test

Electrical and geometrical parameters of $N = 19$ wire bundle considered within this work, see Fig. 1(a), are the following: conductor radius $r_w = 0.4\,\mathrm{mm}$, dielectric jacket radius $r_{die} = 0.8\,\mathrm{mm}$, relative permittivity of the dielectric jacket $\varepsilon_r = 2$, center-to-center wire separation $s = 2.75\,\mathrm{mm}$, height of the cable harness (to the center wire) above ground of the bundle axis $h_w = 47.5\,\mathrm{mm}$, and the bundle rotation angle $\theta_w = 0°$. The bundle length is $\mathscr{L} = 2\,\mathrm{m}$ and the BCI probe is clamped $150\,\mathrm{mm}$ far from the EUT, in accordance with the standard [3]. For validation purposes, each conductor is connected to $50\,\Omega$ terminal loads.

B. Modal Analysis

The multiwire circuit model is decomposed into CM and DMs by means of the transformation matrices $\boldsymbol{T}_V$ and $\boldsymbol{T}_I$ defined in [16]. This definition does not ensure decoupling between modes, and therefore mutual coupling between all modal circuits should be considered. In this framework, a weak coupling assumption is introduced to decouple the CM (which is the dominant mode) from the DMs. Namely, the CM is assumed to excite the DMs, but not to be subjected to any back-interaction. Therefore, the modal impedance, admittance and per-unit-length (p.u.l.) parameters matrices of the overall system exhibit zeros in the DMs-to-CM terms (i.e., j entries, with $1 = \mathrm{CM}$ and $j \neq 1$). The simplification is consistent with the CM nature of the BCI mechanism. Indeed, the current injection is symmetrical in all conductors, whereas deviations in the terminal voltages should be ascribed to asymmetries in the terminal impedance, impedance mismatching with the characteristic one and coupling effects between wires. Thus, equivalent circuits can be derived resorting to single and multi-conductor transmission line (MTL) theory for CM and DMs, respectively (see Fig. 1(b) and (c)). They resort to distributed parameters representations for the TL stretches running outside the probe. Ideally, DM sources are null. In fact, DM circuits are excited through equivalent controlled generators which are accounting for the distributed nature of the coupling along the MTL. The involved current and voltage sources are computed as follows:

$$\begin{bmatrix} \hat{\boldsymbol{V}}_{\Delta,\mathrm{x}} \\ \hat{\boldsymbol{I}}_{\Delta,\mathrm{x}} \end{bmatrix} = \int_0^{\mathscr{L}_\mathrm{x}} \hat{\boldsymbol{\Phi}}^{\mathrm{DM}}_{\mathrm{MTL}}(\mathscr{L}_\mathrm{x} - \tau) \begin{bmatrix} -j\omega \boldsymbol{\Delta\ell} \hat{I}^{\mathrm{CM}}_{\mathrm{x}}(\tau) \\ -j\omega \boldsymbol{\Delta c} \hat{V}^{\mathrm{CM}}_{\mathrm{x}}(\tau) \end{bmatrix} d\tau \quad (1)$$

where x stands for L or R depending on the considered side of the probe (see Fig. 1(b)), $\mathscr{L}_\mathrm{x}$ and $\hat{\boldsymbol{\Phi}}^{\mathrm{DM}}_{\mathrm{MTL}}$ are the length and the chain parameter matrix of the considered stretch of line running outside the probe, respectively. Finally, $\boldsymbol{\Delta c}$ and $\boldsymbol{\Delta \ell}$ are the p.u.l. parameters of the MTL that are accounting for the CM-to-DMs couplings. Additionally, the model include the effect of test fixtures: in the CM circuit, fixture and single-conductor are cascaded obtaining $\hat{\boldsymbol{\Phi}}^{\mathrm{CM}}_{\mathrm{AE,EUT}}$. Instead, equivalent sources are placed in between the MTL and test fixtures in the DM networks. For a detailed description of these models, the Reader is referred to [16]. A comparison between modal and phase terminal voltages predicted by using the reference solution and the two-step procedure in the modal domain are reported in Fig. 2. The comparison shows that predictions obtained by the two-step model are almost overlapping with the reference phase voltages, whereas slight discrepancies are observed in DM predictions. However, the accuracy of the procedure is satisfactory. The agreement achieved in Fig. 2 (a) is due to the inherently CM nature of BCI. Instead, the slight mismatch that can be observed in Fig. 2 (b) is a consequence of neglecting the DM-to-CM back interaction, according to the weak coupling assumption.

C. Hybrid Probabilistic-Possibilistic Uncertainty Evaluation

Mode decoupling allows an insight into the CM-to-DMs conversion mechanism in BCI setups. As a consequence, the effect of physical parameters can be assigned to CM or DMs, which can speed up statistical analyses in case those values are affected by uncertainty. Namely, the decomposition can be applied to identify maximum (upper bound) and minimum (lower bound) noise levels at terminations of the BCI setup. The variability of the considered parameters are modeled both as random variables (RVs) through suitable probability distribution functions (pdf), and as possibilistic variables (PVs) through fuzzy sets [18]. In particular, these last are adopted to account for uncertainty not due to stochastic variability,

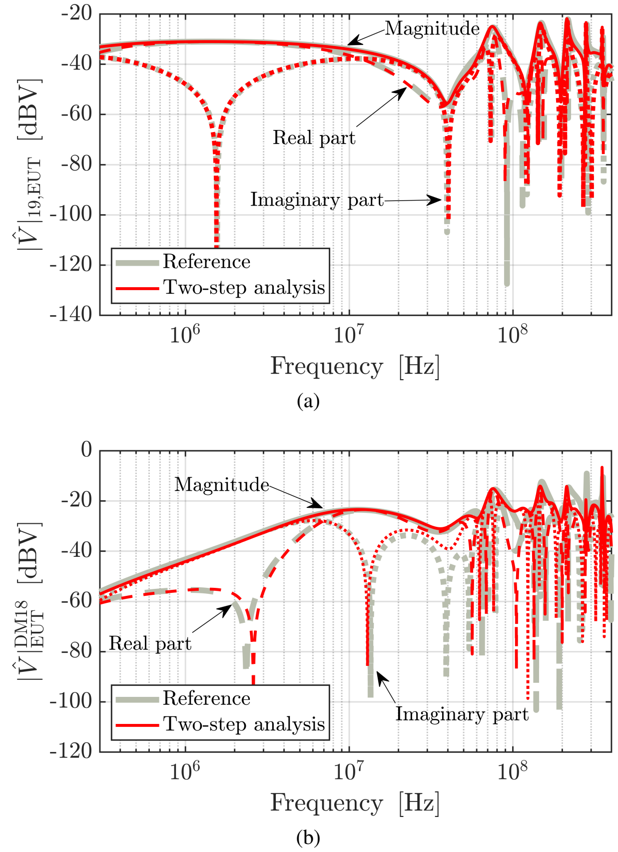

Figure 2. Phase (a) and modal (b) voltages predicted at the terminations on the equipment under test (EUT) side. The two plots show a comparison between the results of deterministic simulations carried out adopting the model proposed in [13] and the two-step procedure on the nineteen-conductor setup considered in Sec. II-A.

but due to an intrinsic lack of knowledge associated with certain variables (i.e., epistemic uncertainty). In this framework, the variability of geometrical and electrical parameters describing the wiring harness is represented through RVs with Gaussian pdfs around their nominal values. The CM equivalent impedance to ground is instead modeled as a PV with uniform possibility distribution. Thus, a hybrid probabilistic–possibilistic algorithms is applied to evaluate the overall uncertainty in the prediction of both modal and phase terminal voltages. Some hybrid procedures can be found in the literature [19]–[21] and some further details on possibility theory can be found in [22]–[24].

III. Proposed statistical approach

This section introduces the proposed method to predict the upper and lower bounds of the BCI test involving a N-conductor wire harness with some uncertainties. Assume that d_C and d_D represent the number of random parameters which primarily determine the performance with respect to CM and DM, respectively. If k_C and k_D are the numbers of required samples for the CM- and DM-linked parameters, $d_C^{k_C} \times d_D^{k_D}$ N-wire sub-problems have to be solved by MTL analysis (see Fig. 3a) in order for upper and lower bounds to be

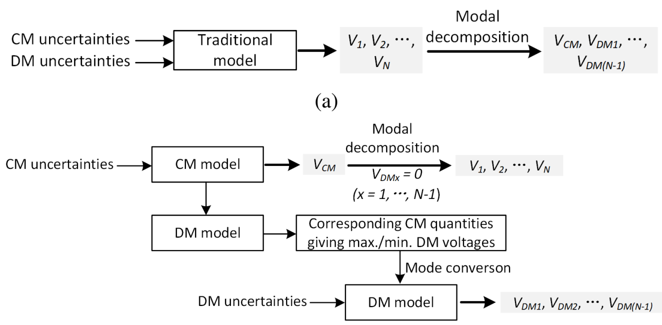

Figure 3. Principle drawings of (a) the reference solution [13] and (b) the proposed approach with the example of voltage predictions

predicted. This computational burden can be mitigated if the problem is investigated in the modal domain with CM and DM equivalent circuits, as analyzed in [16]. In this analysis, the CM and DM equivalent circuits are considered with the corresponding CM- and DM-linked parameters, in which the DM circuits are excited by mode conversion from the CM circuit [16]. This step is simple and provides reasonably good predictions. However, conditions for maximum and minimum CM predictions do not necessarily correspond to the conditions for maximum and minimum DM quantities. Therefore, the idea proposed in this work is to obtain the DM values even when the CM equivalent circuit is analyzed with the random CM-linked parameters. To this end, mode conversion is also considered in the first step of the analysis and it is used to predict DM quantities in correspondence of the *deterministic* and *nominal* DM-linked parameters. Therefore, CM quantities, which are used as the input for the final DM uncertainty evaluation, are associated with the maximum and minimum of the intermediate DM analysis. A principle drawing is presented in Fig. 3b. This approach can improve the accuracy of the DM prediction, at the cost of an increase in computational time, as will be discussed in the following section.

IV. Application Example

The proposed enhanced method is applied to a numerical example in which the BCI probe is clamped on a nineteen-conductor wire harness. Specifically, three RVs related to geometrical uncertainties are considered: $h_w \sim \mathcal{N}(70, 10)$ mm, $r_w \sim \mathcal{N}(0.4, 0.05)$ mm, and $\theta_w \sim \mathcal{N}(0, 6)^\circ$. The three RVs have inherent uncertainties where nominal values are known, but actual values vary according to Gaussian distribution. Furthermore, they mainly affect DM quantities [16] and are therefore treated as DM-linked variables. In contrast, the equivalent CM terminal impedance, which, obviously impact on CM quantities, is determined by several factors such as internal terminal circuit, internal mechanical structure, parasitic capacitance, etc. This impedance is usually unknown to the operator due to lack of knowledge. Therefore, left and right CM terminal impedances $R_{\mathrm{AE}}^{\mathrm{CM}}$ and $R_{\mathrm{EUT}}^{\mathrm{CM}}$ are treated as CM-linked PVs with the rectangular possibility distribution $[0, 1000]$ Ω.

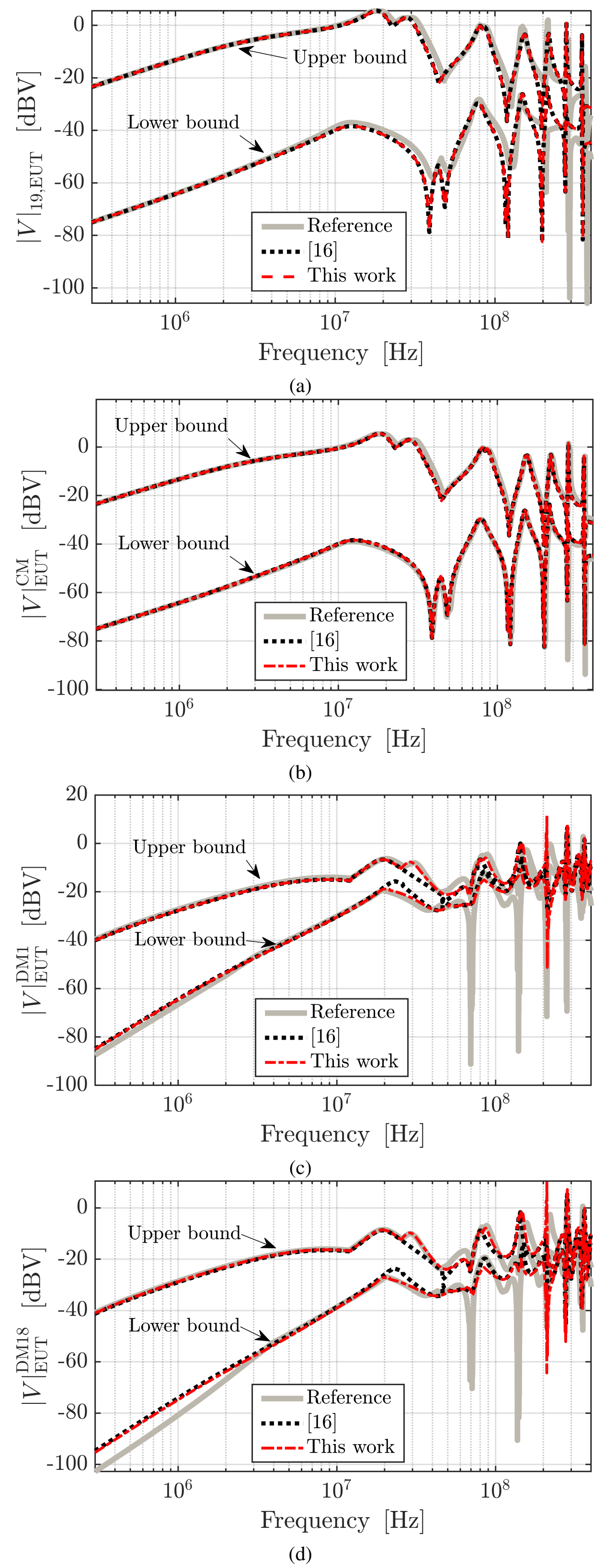

Figure 4. Prediction of upper and lower bounds of (a) V_{19} and (b) V_{CM}, (c) V_{DM1}, and (d) V_{DM18} measured at left side of the nineteen-conductor setup based on the reference solution [13], the technique in [16] and the approach introduced in this work.

Table I
SUMMARY OF COMPUTATIONAL EFFICIENCY

Method	Problem dimension	Computational time
Reference [13]	4000 19-conductor MTLs	8669 s
[16]	400 1-conductor TLs 20 18-conductor MTLs	367 s
This work	400 19-conductor MTLs 20 18-conductor MTLs	1566 s

To predict upper and lower bounds of induced voltages in the aforesaid test setup, hybrid simulation, based on the proposed approach, is carried out. The obtained results are then compared versus the reference solution [13] and the modal-domain approach in [16]. To this end, the harness p.u.l. parameters are computed by a 2D electromagnetic solver. RVs and PVs are addressed by second-order polynomial chaos expansions (PCE) [25], [26] and linear-spaced grid search (GS) methods, respectively. Here, it is worth noting that the settings of PCE and GS are the same in the three approaches. Therefore, there is neither additional discrepancy nor additional computational burden introduced by the statistical algorithms themselves (i.e., PCE or GS). This leads to the same number of runs of the 2D electromagnetic solver, thus easing the comparison between the three methodologies.

Fig. 4 shows the lower and upper bounds predicted by the three methods. The method in [16] generally provides satisfactory prediction. However, it is outperformed by the proposed approach, which is proven to provide more accurate predictions of DM voltages, especially in the medium frequency range $20\,\mathrm{MHz} - 100\,\mathrm{MHz}$. Physical and CM voltages are not significantly affected, as can be noted in Fig. 4 (a) and (b).

Concerning computational efficiency, the computational cost of the statistical algorithms and the numerical simulations of the p.u.l. parameters are identical for three methods. The advantage of the two-step procedure lies in the fact that it requires the solution of a smaller number of MTL equations. In this application example, 400 samples and 10 samples are considered for GS and the PCE-based models, respectively. To predict upper and lower bounds of DM voltages, the reference solution deals with 4000 nineteen-conductor MTL problems and needs $8669\,\mathrm{s}$. The two-step procedure in [16] only requires $367\,\mathrm{s}$ to solve the MTL problems, which include the solution of 400 one-wire CM TL problems and 20 eighteen-conductor DM MTL problems. The proposed approach (400 nineteen-conductor and 20 eighteen-conductor MTLs) requires $1566\,\mathrm{s}$ for computing MTL problems, which are actually larger than those in [16]. However, it is still considerably faster than the traditional method on the one hand and provides higher accuracy with respect to [16] on the other hand. Data on computational efficiency are compared in Table I.

V. Conclusion

This paper proposed a modal-domain two-step approach adapted from the method in [16] for predicting upper and lower bounds of noise levels induced at the terminations of BCI test setups involving multi-wire harnesses. The key feature of the proposed method is the use of DM-related information, rather than purely CM information, in the mode conversion procedure. The presented simulation results proved that the proposed approach can provide higher accuracy in predicting DM quantities compared to [16], at the cost of an acceptable increase in the computational burden. As a matter of fact, the proposed method is still considerably faster ($\times 5.5$) than the traditional MTL-based method, thus offering a very good compromise between computational efficiency [16] and prediction accuracy (reference solution).

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