dr hab. inż. Łukasz Jankowski, prof. IPPT PAN
Zakład Technologii Inteligentnych
Instytut Podstawowych Problemów Techniki PAN
ul. Pawińskiego 5B
02-106 Warszawa
email: ljank@ippt.pan.pl

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Review
of a PhD thesis of Mr. Shishir Kumar Singh, M. Tech. Eng. titled „Electromechanical impedance-based damage detection and localization employing data Fusion techniques”

1. Legal basis

The legal basis for this review is the letter No RN-421-2/33 sent by Prof. Grzegorz Żywica, Director for Research of the Institute of Fluid–Flow Machinery of the Polish Academy of Sciences (IMP), dated July 28, 2023, and the attached PhD thesis of Mr Shishir Kumar Singh titled “Electromechanical impedance-based damage detection and localization employing data Fusion techniques.”

The thesis was written in the Department of Mechanics of Intelligent Structures IMP PAN. The supervisor of Mr. Shishir Kumar Singh is Prof. Paweł Malinowski.

2. General topic and aims of the dissertation

The general aim of the dissertation is formulated on page 17 as follows:

> *The major aim of this thesis is that it can provide robust data-driven data-fusion based approaches to enhance damage detection and localization performance for metal, composite and 3D printed structures.*

There are four specific aims, which are stated as follows (page 17):

1) *…the first objective of this research is to improve structural damage detection performance by sensor level or variable level data-fusion analysis in the frequency-domain EMI responses from piezoelectric transducers.*
2) *..this study’s second goal is to develop a theoretical data-driven approach for the proper selection of frequency ranges.*
3) *The third objective of this thesis is to expand from damage detection to damage localization by accurately imaging the single and multi-damaged locations using the data fusion technique.*
4) *The fourth objective of this research is to reduce the measurement time using series and parallel combinations of the impedance analysis electrodes for damage detection based on analyzing the frequency-domain responses from piezoelectric transducers. This research is also conducted to investigate the effects of temperature variation on the different type connections to verify the performance.*

Finally, the formal thesis of the dissertation is threefold and defined as follows (page 17):

- *The data fusion techniques are enhancing performance compared to the conventional approach for damage identification.*
- *Sensor network-based damage localization accurately predicts single and multi-damage locations.*
- *A data-driven theoretical effective frequency range selection is possible that enhances the performance of data fusion-based damage detection and damage severity quantification*

The general aim and the specific aims have been formulated correctly and relatively precisely. The topic belongs to an important research area that is related to nondestructive testing (NDT) techniques and their applications for identification, localization and quantification of local structural damages. This area is under an intense development worldwide, and important in both research and practical terms. The specific subfield of data fusion techniques, which is the main subject considered in the thesis, is definitely timely and at the forefront of research. Therefore, the reviewer considers the research problems discussed in the dissertation timely, challenging, and interesting. They are important from both a research and practical/applicational point of view. Undertaking research in such a specific topic is fully justified.

3. Content of the dissertation

The dissertation is written in English. Its main part consists of 122 pages. The structure of the dissertation is logical, clear, and well-suited to the presented content. Its essential part is contained in Chapters 2–5, which are preceded by a brief summary in English, list of author's journal and conference publications related to the thesis, lists of figures and tables, and an introduction, and followed by a conclusion and a bibliography. The bibliography comprises 131 entries, including 7 articles by authors associated with the Doctoral Candidate's research environment (employees of IMP PAN). The Doctoral Candidate has co-authored 8 related journal papers listed in the bibliography and/or in a separate list at the beginning of the thesis, and in 2 of them he has played the role of the corresponding author. These articles were published in reputable international scientific journals such as *Structural Health Monitoring*, *Composite Structures*, *Journal of Intelligent Material Systems and Structures*, and *Smart Materials and Structures* between 2019 and 2023. The current impact factors of these journals range from 2.7 to 6.6 (average 4.7). It should be emphasized that so far, in a relatively short time, these 8 papers have attracted 75 external citations (without self-citations, according to Web of Science). Such bibliometric indicators are significant at this stage of the academic career. Such a publication track record indirectly confirms the quality of the Candidate's research work.

Chapter 1 (*Introduction*) is, as the title suggests, a general introduction to the subject of the dissertation. The Doctoral Candidate describes the motivation of the dissertation, characterizes the research gap, formulates the objectives, and presents the structure of the thesis. The chapter presents also the literature background, from the broad topic of piezoelectric materials in structural health monitoring (SHM), down to the specific area of data driven SHM using the technique of electromechanical impedance (EMI).

The subsequent four chapters of the dissertation (Chapters 2–5) are devoted to its four specific aims listed in the introduction.

Chapter 2 (*Damage detection via data fusion of PZTs based on series and parallel connections*) considers the data fusion at the lowest possible level, that is at the raw hardware level of sensors (aim 4). The Doctoral Candidate tests and compares the results obtained with four combinations of two sensors: two single sensors considered separately, a parallel combination, and a series combination.

Chapter 3 (*Variable and sensor level data fusion based damage detection*) deals with the first specific aim (aim 1), that is with damage detection procedures that utilize measurement-level and data-level fusion. Two general approaches are proposed and tested: a direct fusion of two specific EMI signals in frequency domain, and a few techniques based on the principal component analysis (PCA) and self-organizing maps (SOM).

Chapter 4 (*Sensor network based damage imaging*) considers damage imaging, that is localization of damage, which is an SHM step subsequent to the detection of damage. Two approaches are discussed and tested in examples. There is a broad introduction to and a discussion of direct imaging techniques, and a proposal of an inverse technique. This chapter correlates with the third specific aim (aim 3) listed in the introduction.

Chapter 5 (*A standard deviation approach in damage detection*) introduces and tests a quantitative technique for selection of frequency range most suitable for EMI-based damage detection.

Chapter 6 (*Conclusions and future work*) summarizes the dissertation and the major original achievements, and mentions potential further research directions.

4. General assessment of the dissertation

The doctoral dissertation under review is dedicated to a research topic that is both current and original, and with a significant practical relevance. The Doctoral Candidate has demonstrated a sound use of the research methodology within his discipline: (1) beginning by outlining the broad context and available techniques, subsequently, (2) discussing the research gap and formulating specific objectives, and then (3) describing the four newly proposed techniques and reporting on the experimental verification, and finally, (4) presenting general conclusions, summarizing the major achievements, and suggesting possible future research directions. Such a research framework, well-reflected in the structure of the dissertation and generating a good publication track record, confirms the academic maturity of the Candidate.

The subject of the dissertation belongs to the rapidly evolving research field related to the nondestructive testing of engineering elements for the purpose of detection and imaging of their local damages. In particular, the dissertation is related to data processing techniques. The reviewer would like to specifically emphasize the following elements as important, interesting, and significantly original achievements of the dissertation:

- A methodologically interesting and sound division of data fusion techniques into three levels: hardware/sensor level, measurement level, and data level. Subsequently, at each of these levels, the Doctoral Candidate proposes specific methods, discusses them and verifies using experimental data.
- Detailed analysis of the effectiveness of the analyzed hardware-level data fusion approach, especially including its robustness with respect to temperature changes.

- Proposal, demonstration of an application, and verification of specific indices for damage detection based on the PCA analysis.
- Formulation and experimental verification of damage imaging techniques, and especially of the technique based on the inverse formulation.

The broad scope of the proposed and investigated techniques, as well as the evidently substantial effort required for conducting their experimental verification, leave a very positive impression.

5. Comments

The reviewer did not notice any significant errors or omissions in the dissertation. Essentially, all the relevant partial results and techniques presented in the dissertation have already undergone a substantive review process, since the Doctoral Candidate has presented them in 8 papers published in reputable journals.

The comments and questions provided below are meant to be more of a discussion or clarifying nature than the critical nature. Their general intention is to potentially contribute to improving the clarity and instructional value of the dissertation.

1) Even it does not directly affect the research content and value, an important shortcoming of the dissertation seems to be the its sometimes chaotic manner of exposition. The reader often struggles with unfinished sentences or incomplete thoughts and is forced to browse back through numerous pages to find fragmented information. Sometimes following the exposition has to be facilitated by consulting the related journal publications.
2) The results presented in Chapter 2 suggest that the parallel combination of two sensors is more effective than their serial combination as well as the repeated use of a single sensor. The reader misses an attempt at a higher-level explanation and analysis: What are the reasons and the consequences? Why is the p12p combination more sensitive to damage but less sensitive to the temperature? How this result could be utilized further, for example, to decide the number and placement of several sensors?
3) Figures like Fig. 2.7 show first the baseline (green), which is computed using two measurements taken in the healthy state of the specimen, and then the results obtained by comparing the measurements taken in the damaged state with the measurements taken in the healthy state (red). However, there are at least two healthy-state measurements available: which one of them is used? Does this choice affect the height of the red bars?
4) Table 2.2 lists only selected combinations of temperatures for the healthy- and damaged-state measurements. It seems that all necessary measurements are available: why are not all combinations shown?
5) Figs. 2.11–14 show the damage detection results for the four tested sensor combinations. Only in the p12p combination, the indices in the damaged case (red) are noticeably larger than in the healthy case (green). Still, the difference is not large, and the reader may wonder what is the natural variability of the (green) thresholds and the (red) indices. Should not a statistical analysis be performed, and the detection probability assessed using the standard deviation values? Similar remarks (lack of a statistical analysis) apply also to the results shown in Chapter 3.2.
6) The dissertation seem to use EMI signatures like G and R without formally defining them. Even if standard in the literature, they should be explicitly introduced.

7) The definition of the data processed for PCA in Chapter 3.3.2 is not clear. What data vector is considered in PCA? Are signals from only a single sensor taken into account or from all sensors at once?
8) Figs. 3.14–15: the reader misses the reference levels computed in the healthy-to-healthy case.
9) The selection of sensors suitable for damage localization described in page 69 seems to be performed a posteriori, that is with respect to an already known damage. Can a similar procedure be applied before monitoring, to determine suitable sensor location with respect to a certain set of potential or expected damages?
10) Chapter 4.3: only a single example is used for verification. The reader misses a broader verification, with a larger number of examples, as these shown in the previous sections.
11) The methodology for frequency range selection described in Chapter 5 is effective. However, it requires measurements collected in an already damaged state. It is not clear, how and if it can be applied also a priori, that is before the occurrence of any damage or when the existence of damage is unknown.
12) The reader lacks any interpretation of p1, p2, and C defined in eqs. 5.6–8.
13) The min and max values shown in Fig. 5.24 suggest that the underlying distribution is far from Gaussian. Could the Candidate offer a comment on that?

6. Technical and editorial remarks

- In the initial list of related publications of the Candidate, the first publication (in Structural Health Monitoring) is listed with "0(0)" as the volume and issue numbers, and without the doi handle. It is relatively obvious that this publication was in the "accepted yet not published" state at the moment of submitting the thesis, but it should be stated explicitly for clarity.
- The first line of text below equations is almost always intended. These lines should not be intended unless they indeed start a new paragraph.
- Figures like Fig. 1.5–7 or 2.5 would be much better readable, if the vertical axis was log-scaled.
- Should not Fig. 2.3 include subfigure d) with the cracked beam case?
- Many figures would be easier readable, if their captions provided more information, including explanation of the symbols used in the legend. For example, this applies to the legend of Fig. 2.7 or to the symbols in Figs. 3.4–9 (which seem not explained even in the text).
- Eqs. 3.4: The meaning of the symbols f and f_{max} should be explicitly stated. Given the definition of F, the detrending of F seem inconsistent with the detrending of G and R. Why?
- The explanation of the dimensions JxI below eq. 3.6 is unclear.
- The explanation above Fig. 3.12 related to the SOM is unclear.
- Does the distinction between x and bolded x in eqs. 3.9–10 convey any meaning?
- The paragraph below Fig. 4.2 is not clear. For example, the reader misses a clear explanation of the variable r.
- Eq. 5.4 describes a derivative in a continuous setting. However, the data seem to be discretized to the time steps.
- The arguments of p in eq. 5.5 seem a bit strange. Why are not A, sigma, and mu listed separately? On the RHS, they appear independent from each other.
- What does the D-s bar in Fig. 5.12 stand for?
- The values listed for G(S) in Table 5.1 seem inconsistent with Fig. 5.14. Why?
- The label of the horizontal axis in Fig. 5.22 seem wrong.

7. Conclusion

The doctoral dissertation of Mr. Shishir Kumar Singh is devoted to a timely stream of research within the field of nondestructive testing: the approaches based on data fusion. The results achieved are original and of interest for the general scientific community, as attested by the relatively large number of external citations of the related publications. All the critical remarks provided in this review are only technical in nature.

The reviewed work satisfies the formal and customary requirements for doctoral dissertations. It offers an original solution to a scientific problem and demonstrates the Candidate's general knowledge in the field of mechanical engineering, as well as his ability to conduct research independently. In particular, the thesis meets the requirements set by the applicable law (Ustawa z dnia 20 lipca 2018 r. Prawo o szkolnictwie wyższym i nauce, Dz.U. 2023 poz. 742). I recommend that the dissertation is allowed to proceed to further stages of the doctoral proceedings, including the public defense.

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