

Wiesław Wszółek, PhD, University Professor  
AGH University of Kraków  
Faculty of Mechanical Engineering and Robotics

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## **Review of a doctoral dissertation**

The subject of the review is a doctoral dissertation entitled *Vehicle Diagnostics using Artificial Intelligence and Digital Signal Processing Methods*. The author of the reviewed dissertation is **Muhammad AHSAN**, MSc, and his supervisor was **Professor of the Silesian University of Technology, Dariusz BISMOR, PhD**.

### **Formal basis for the review:**

The review of the doctoral dissertation of Muhammad AHSAN, MSc, was prepared on the basis of the order of the Silesian University of Technology (contract for work No. 06.08/PRR/2024 for the preparation of the review) represented by Prof. Dariusz Kania, PhD, Eng.

### **Comments on the choice of subject matter**

The quality of human life in the private and professional fields is strongly dependent on the use of vehicles, mainly as means of transport. This dependence implies the need to develop effective vehicle fault diagnostic systems to ensure reliability, reduce emissions and maintain the mechanical integrity of vehicles. The task of any diagnostics and especially of technical diagnostics of means of transport is to develop methods and ways to address the issues of assessing the technical condition of vehicles and machines, detecting faults and predicting future failures and qualifying them or their assemblies for further adjustment, repair or even salvage. For the last few years, there has been an intensive development of methods of diagnostic testing of machinery and equipment, based on the available results of observations of the operation of those objects and observations of the interactions occurring between the objects and their environment. A particular development has been observed in the field of vibroacoustic diagnostics. Diagnostic techniques based on vibroacoustic signals have gained importance as an alternative approach to fault detection, since vibration signals as information carriers contain a lot of information about the dynamic behaviour of mechanical systems. Furthermore, the observed intensive development of signal processing and analysis techniques has significantly increased the effectiveness of vibration signal-based diagnostics.

I believe that the presented theme of the work is legitimate. Efforts to improve that process also with the use of new measurement transducer technologies and artificial neural network techniques are therefore justified.

### **Preliminary remarks**

The dissertation presented for evaluation is quite extensive at 155 pages, it is written in English, has a classical layout and its content is logically divided into 6 chapters, including an Introduction and a Summary and four appendices. The work is also nicely supplemented by a

list of sources used ("Bibliography"), including 126 well-chosen and up-to-date literature items, abstracts in Polish and English, a list of figures (85) and tables (20), as well as a separately presented list of the Doctoral Candidate's publications from the ministerial list (4) and from conference proceedings (4). Most of the figures included in the dissertation, represent the original results of the research carried out by the Doctoral Candidate. I assess the structure of the dissertation as very good.

### **Research issue**

A doctoral dissertation evaluation usually begins with an assessment of the research hypothesis (or its equivalent) that the Doctoral Candidate wishes to prove with their dissertation, thus introducing a new result into the resources of world science. It is usually expected that this scientific assumption will appear at the beginning of the dissertation. Such an approach enables the reviewer to determine what the author is aiming at and which parts of the dissertation aim at indicating the truth of this assumption. Unfortunately, this aim in the reviewed dissertation is referred to not earlier than on page 21. When the reviewer reaches the chapter "Research objectives", they find that 3 objectives were presented. The second objective focused on the application of DSP techniques to the analysis of vibration signals for fault diagnosis. And finally, the third one presented by the Author of the dissertation as the final objective, which is the use of machine learning methods to improve the accuracy and reliability of engine ignition interval diagnostics. I acknowledge and appreciate that Muhammad AHSAN, MSc, has clearly presented the purpose and scope of his research. Based on the formally presented purpose of the dissertation and the manner in which it has been achieved, there is no doubt that the research question addressed in the dissertation under review, in terms of the scientific significance of the proposed research and the practical usefulness of its results, meets the statutory and customary expectations placed on doctoral dissertations, which I fully accept.

### **Analysis of literature sources**

The author of the evaluated doctoral dissertation has demonstrated a great erudition and ability to combine many scientific fields, undoubtedly, he has extensive and modern knowledge in the problem area that is the basis of the scientific research he has undertaken in his doctoral dissertation. Evidence of his wide erudition is provided by the content of Chapter 1, where first the literature positions on the research object and the methods used to diagnose it, based on new hardware and computing technologies, are discussed. Confirmation of this broad knowledge is also presented in further subsections and chapters of the dissertation. Initially those literature items concerning professional methods of measuring non-electrical quantities by electrical methods are discussed, with a particular discussion of transducers made with MEMS technology and their use in the recording of vibration signals. Secondly, information taken from the literature on signal processing methods in the following domains: time, frequency and time-frequency, useful in the search for distinguishing features necessary in diagnosing engine operating states during misfire and bearing faults, is presented. This is followed by an analysis of the usefulness of artificial intelligence techniques in signal analysis and engine diagnostics.

Having studied this material contained in the initial chapters of the dissertation, I can conclude that the PhD candidate has knowledge of the works of other authors dealing with issues similar to the one he is carrying out with his own research. He is also able to draw appropriate conclusions from the literature, drawing inspiration from it for his own scientific concepts and further research.

### **Analysis of the original part of the dissertation**

Presenting his own research and its results, Muhammad AHSAN, MSc, started with introducing the first step of the research implementation (in Chapter 2) which is a thorough analysis of the operation of the measurement system used in further research. The chapter described the structure of the measurement system using the ADXL1002 accelerometer working with the BeagleBone Black controller. The PhD Candidate presented a proposal for the calibration of the measurement system as well as an analysis of the causes of errors. The description of the system setup and calibration is solid. However, I have some comments on this chapter, which I will present in the final part of the review.

The next chapter (Chapter 3) deals with the acquisition of vibration data obtained at the test stand in the Vehicle Vibration Laboratory at the Faculty of Transport, Silesian University of Technology. The measurement system discussed in Chapter 2 of this dissertation was used for vibration data acquisition. In this chapter, the Doctoral Candidate presented in detail the course of the experiment (operating states of the object - the car engine) and also emphasised the importance of accurate collection of measurement data. The chapter contains a detailed analysis of vibration data sets obtained from measurements on the test stand developed by the Doctoral Candidate (vibrations caused by engine ignition malfunctions), as well as the NASA data set (vibrations caused by selected bearing malfunctions), emphasising their key role in the analysis and diagnostics of mechanical systems. In presenting a description of the data acquisition experiment, the PhD Candidate demonstrated his ability to prepare the scientific workshop well before commencing further research.

The description of the research methodology, the set-up of the diagnostic data acquisition experiment, is sound. Overall, my assessment of this chapter is overwhelmingly positive.

Chapter 4 is also key to the assessed dissertation. In it, the Doctoral Candidate presented his research results, which are crucial to ensure the reliability of the engine's operation and the safety of its use. Vibration signals, originating from internal combustion mechanisms and rotating components such as bearings, are a rich source of diagnostic information. The parameters contained in these signals enable accurate detection of faults such as misfires and bearing failures. The author used a variety of Digital Signal Processing (DSP) techniques to extract relevant diagnostic information from the collected vibration signals and prepare the data for further analysis. These methods were aimed at isolating and amplifying fault signatures, minimising the impact of noise and preparing the data for artificial intelligence models. The author presented a comprehensive analysis of advanced DSP techniques for fault diagnosis using both bearing data sets and vehicle engine misfire data sets. By applying these methods to diverse and complex vibration signals, the Author demonstrated their effectiveness in identifying fault-specific features, whether related to bearing defects or engine ignition

interrupts. Among the novel signal processing and analysis methods used in the diagnosis of the object described in the paper, I can include; adaptive bandpass filter (BPF) optimisation based on the Harmony Search Algorithm (HSA) and engine ignition interruption diagnostics based on empirical mode decomposition (EMD) and first intrinsic mode function (IMF) analysis. These novel DSP methods, combined with appropriate data acquisition hardware (an ADXL1002 accelerometer and a BeagleBone Black controller), provide the basis for advanced vehicle diagnostic systems capable of dealing with the complexity and non-stationary nature of real-world vibration signals. This chapter presents several novel digital signal processing (DSP) methods for diagnosing vehicle faults. They focus on the precise detection of bearing faults and engine misfires through the analysis of vibration signals. Empirical material has been collected and systematised, which is an important scientific contribution of the PhD Candidate, which I greatly appreciate.

Another important element of the assessed dissertation is Chapter 5. The issues that Mr Muhammad AHSAN, MSc, "gets to grips with" in this chapter are those that he has previously made the subject of his experiments, discussing the results of his research against an extensive and well-chosen literature background. He makes the following question the subject of discussion: does combining artificial intelligence techniques with a diagnostic framework significantly improve fault detection capability, offering more accurate, reliable and scalable solutions for vehicle diagnostics that go beyond the capabilities of traditional signal processing methods?

The author presented and analysed artificial intelligence (AI) methods based on artificial neural networks used in vehicle diagnostics, with particular emphasis on engine misfire detection based on information contained in vibration signals. The analysis focused on the influence of the topography of the neural model as well as its learning process on the correctness of distinguishing features and fault classification. These methods focus on the ever-evolving techniques of artificial intelligence (AI) in vehicle diagnostics, with particular emphasis on the detection of engine misfires also based on information contained in vibration signals. They aim to minimise the limitations of traditional diagnostic techniques by offering automatic feature extraction, precise pattern recognition and adaptive learning. Among the most important achievements presented by the PhD Candidate in this chapter are: the introduction of advanced deep learning network architectures, especially Multi-Kernel-DCNN-LST models (chapter 5.6), the suitability of the representation of 1D and 2D data in terms of diagnostic accuracy, particularly evident in the Multi-Kernel-DCNN-LSTM model, making a comparative analysis based on simulation results for each model (DCNN, DCNN-LSTM, Multi-Kernel-DCNN-LSTM) using both 1D and 2D data, assessing their accuracy. The material contained in this chapter is an important scientific contribution by the PhD Candidate, which I greatly appreciate.

Obviously, Conclusions contained in Chapter 6 are the most important element of the evaluated dissertation. It is generally accepted in dissertation evaluations that the conclusions presented in the chapter summarising the achievements in the realised dissertation are a confirmation of the hypotheses contained therein. Unfortunately, in the work under review, the dissertation's hypotheses were not overtly presented. As a result, the reader has to study chapters (e.g. 1, 2, 3) again to read these hypotheses.

The main achievements and conclusions presented in the reviewed dissertation are:

1. Confirmation of the feasibility and effectiveness of the MEMS ADXL1002 accelerometer in vehicle vibration diagnostics.
2. Development of a comprehensive process for vibration data acquisition and pre-processing.
3. Significant development of artificial intelligence methods for fault diagnosis, minimising the limitations of traditional DSP methods.
4. Development and implementation of advanced DSP algorithms (e.g. adaptive filter optimisation using Harmony Search Algorithm (HAS) and Particle Swarm Optimisation (PSO), as well as IMF-based FFT) for bearing and engine fault diagnosis in vehicles.
5. Practical implications and future research directions.

The research paves the way for the development of scalable and cost-effective diagnostic systems for the automotive industry (and others, such as aerospace, manufacturing), contributing to increased operational efficiency, reduced downtime and increased reliability of mechanical systems.

Furthermore, the research has shown the feasibility of using low-cost sensors, such as the ADXL1002 accelerometer, in combination with advanced artificial intelligence models. This combination represents a promising approach for developing scalable and cost-effective diagnostic systems for the automotive industry.

**In summary, I conclude that the aim of the dissertation has been achieved.**

#### **Editorial comments**

The dissertation is written correctly, but I noticed minor editorial faults in a few places, which I am obliged to point out. One shortcoming is the failure to provide an index of the designations used in the dissertation (and there are many), which makes it difficult to read and analyse the text.

A general remark concerning figures: 1.6, 1.7, 1.8, 2.11, 4.2, 4.3 to 4.25, 5.2, 5.3. In these figures there is no description of the units on the vertical axis.

Figures 4.2 to 4.13: what do the given fault signal numbers mean? (e.g. "fault signal 6075", "vibration signal 1598").

Pages 70 and 71: no numbering of the formulae which appear in the other chapters.

Graphs 4.19 to 4.24 show the results of the FFT analysis, the author does not give the parameters of this analysis.

#### **Questions**

1. In chapter 2.3, you presented the calibration procedure for the ADXL1002 accelerometer. Figure 2.7 shows a proposed measurement set-up for calibration. What is missing from this system is a reference measuring transducer from which you can take a reading of the output signal from the exciter, both frequency (e.g. in Hz) and amplitude (e.g.  $m/s^2$ ). Therefore, what you have recorded at the output of the ADXL1002 cannot be compared to the standard. You have not mentioned anything about what device the measurement amplifier is taking the signal from.
2. Please discuss the usefulness of using Kalman filtering in engine diagnostics.

## Evaluation of the dissertation

Moving on to the final evaluation of the dissertation, I conclude that, taking the above into consideration, the reviewed dissertation by Muhammad AHSAN, MSc, entitled "*Vehicle Diagnostics Using Artificial Intelligence and Digital Signal Processing Methods*" fulfils the conditions for a doctoral dissertation, in accordance with Article 187 of the Act of 20 July 2018 "Law on Higher Education and Science", Journal of Laws of 2022.06.07. Enumerating the statutory conditions one by one, I can state the following:

1. The doctoral dissertation demonstrates the candidate's general theoretical knowledge in the discipline or disciplines and the ability to conduct scientific or artistic work independently. **Fulfilled.**
2. The subject of the dissertation is an original solution to a scientific problem, an original solution to the application of the results of scientific research in the economic or social sphere, or an original artistic achievement. **Fulfilled.**
3. A doctoral dissertation may be a written work, including a scientific monograph, a collection of published and thematically related scientific articles, a design, construction, technological, implementation or artistic work, as well as an independent and isolated part of a collective work. **Fulfilled.**
4. An abstract in Polish is attached to the doctoral dissertation, and an abstract in Polish is also attached to the doctoral dissertation prepared in a foreign language. If the doctoral dissertation is not a written work, a description in Polish and English is attached. **Fulfilled.**

Taking into account the above constataions, I apply to the High Council of the Scientific Discipline, Automation, Electronics, Electrical Engineering and Space Technologies of the Silesian University of Technology to accept the dissertation and admit its Author, Muhammad AHSAN, MSc, to its public defence, and after its positive completion, I will vote in favour of awarding him the doctoral degree.