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ON RESEARCH AND TRAINING IN MACHINERY DIAGNOSTICS IN ENGINEERING EDUCATION

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Abstract

We have a decades-long tradition of examining the operation and maintenance issues of mechanical engineering systems at the Faculty of Engineering at the University of Debrecen. In the last decade, technical diagnostic research has come to the fore, especially bearing diagnostics, a lot of experience has been gathered in this field and many results have been achieved. With the development of the tools of technical diagnostics, the presentation of the topic at all levels of engineering education, and the establishment of industrial relations, an environment has been created in which it is possible to answer the current questions on the topic. Technical diagnostics, which is largely applied informatics (and mathematics) – together with several other engineering topics – also raises educational questions, which we intend to answer by transforming some elements of the training.

Keywords*:* *engineering education, technical diagnostics, teaching engineering mathematics.*

1. Introduction

There is a decades-long tradition of examining the operation and maintenance issues of mechanical engineering systems at the Faculty of Engineering at the University of Debrecen. In the last decade, technical diagnostic research has come to the fore, especially bearing diagnostics, a lot of experience has been gathered in this field and many results have been achieved. With the development of the tools of technical diagnostics, the presentation of the topic at all levels of engineering education, and the establishment of industrial relations an environment has been created in which it is possible to answer the current questions on the topic, including the integration of technical diagnostic tools into digitized manufacturing and operating systems, with a focus on the use of smart devices, machine-to-machine communication, process monitoring (replacing classical condition monitoring) and real-time diagnostic-based applications. Technical diagnostics, which is largely applied informatics (and mathematics) – together with several other engineering topics – also raises educational questions, which we intend to answer by transforming some elements of the training.

2. The role and tools of technical diagnostics

2.1. The role of technical diagnostics

The quality of maintenance is a key determinant of productivity and profitability in the operation of manufacturing companies. The use of the latest tools in technical diagnostics can provide a significant advantage by effectively supporting predictive maintenance, which appears in high levels of availability and machine condition and low frequency of unexpected breakdowns.

The possibilities of technical diagnostics have always been determined by the state of the art of measurement tools (electronics, computing: data transmission and storage capacity, signal processing algorithms), which have evolved along with IT. Because of its crucial role in profitability, technical diagnostics has always been one of the fastest to adopt new IT solutions, for which industrial funding has been (and will continue to be) constantly guaranteed.

The high level of automation in industrial production, the use of high-performance machinery and high productivity requirements further increase the importance of technical solutions that enhance the reliability of the processes.

Diagnostic tools and data are becoming integrated parts of digitalised production systems and smart factories. Moreover, the experience gained in condition monitoring and computer aided maintenance management systems forms the basis for such developments.

2.2. Levels of vibration diagnostics

Vibration-based condition monitoring is the most widely and effectively used diagnostic method.

Based on the purpose, the 'subtlety' of the tools, and the value of the information provided by the investigations, three fundamentally different levels of vibration diagnostics can be identified.

The simplest test is to determine the "vibration level" based on average values (most commonly the root mean square – RMS – of the vibration velocity) or peak values (such as peak or peak-to-peak). At this level, the severity of the overall condition of the machinery can be determined, and failures cannot be identified. If the vibration exceeds a given 'alarm level', the machine should be stopped and the cause of the increased vibration level should be investigated. For example, the ISO 2372 and ISO 10816 standards define general vibration velocity levels for different classes of machinery, which, if exceeded, are a warning to the operator. These limits are independent of the operating conditions and age of the machine; they are for information purposes only. For machines where high-energy vibrations 'only' lead to a reduction of the life-time of certain components, but do not affect operation in the short term (e.g. in the case of subordinate electric motors, pumps), information about the severity (or, preferably about the aggravation) of the vibrations may be sufficient to take the necessary maintenance decisions.

Condition monitoring tools based on vibration measurements are now widely used and are based on the detection of failure symptoms. Their application represents the second level, where the aim is to identify typical failures of machinery as early and as accurately as possible. The key issue here is the detection at the right time which means that corrective intervention is possible in the period between the detection of the fault and its aggravation leading to a breakdown. The length of this period can be a few days or a half a year depending on the process. In the case of a high-performance automatic machines, the critical time may be as short as a few minutes and real-time interventions based on diagnostic measurements may be needed to control the production process (to stop the process or to correct the malfunction).

Symptoms of most mechanical and many electrical failures are specific patterns (line systems) in the frequency spectrum, but some statistical features calculated from the time signal can also be effective in detecting certain problems. A particularly important area is the application of the shock pulse method in bearing diagnostics and gear diagnosis.

Modern condition monitoring systems are able to identify a wide range of faults and determine their severity, based on the symptoms. This information allows maintenance activities to be optimised.

The third level is represented by specific tests using special methods. Available systems and signal processing algorithms provide a detection method for a given set of failures. Otherwise, new solutions in the measurement system and in the processing algorithms are required. For example, in bearing diagnostics alone, hundreds of specialised diagnostic methods have appeared, including an increasing number that use specific combinations of transformations, filtering methods and machine learning tools.

For example, a doctoral thesis **[1]** provides a method for detecting grinding defects and estimating the size of defects in the manufacture of tapered roller bearings, which is effective in noisy environments as well. In the thesis, the design and application of special wavelets and MRA are the basic tools, but also support vector machines and artificial neural networks are used to classify manufacturing defects.

2.3. Evolution of technical diagnostics tools

Since the 1950s, the tools of technical diagnostics have evolved from sensory diagnostics to automated testing and decision-making based on machine-to-machine communication in digitalised manufacturing.

In the old days, given low level of the productivity requirements and the precision of the machines, reactive maintenance (run-to-failure operation) was acceptable. This approach was replaced by preventive (scheduled) maintenance based on life-time characteristics, such as failure rate diagrams ('bath curves') which were prepared on the basis of large statistical samples for commonly used machines (e.g. electric motors).

An obvious limitation of the effectiveness of this statistical approach was that it could not take into account the specific operating conditions leading to a high risk of too early or too late intervention.

With the advent of IT tools becoming available to industry, it was possible to implement condition-based predictive maintenance and develop in-service condition monitoring tools.

The development of technical diagnostics has been uninterrupted since the 1970s, and today online systems, wireless sensors, remote diagnostics, continuous data reporting, diagnostics-based process monitoring, IoT diagnostics tools as an integrated part of digitalised manufacturing systems are widespread in smart factories.

Until the 1980s, the development of maintenance was mainly driven by technical development, but later on, organisational approaches such as reliability-based maintenance, risk-based maintenance or TPM, as well as computer-based maintenance management systems, became increasingly important.

Today, in the era of Industry 4.0 and digitalisation, technical development is again the basis for progress, but these are mainly IT-based developments, as opposed to the mechanical and electrical developments of the past.

3. Teaching technical diagnostics

3.1. The changing role of mathematics in engineering education

The demands of modern engineering, especially the need for the widespread use of machine learning tools, are putting mathematics and its teaching in a new position.

In engineering courses, which are trying to keep pace with the rapid changes in technology, more and more subjects are already appearing in undergraduate engineering courses, which rely heavily on certain higher-level abstract mathematical skills. Examples of such topics are engineering diagnostics and control theory.

Meanwhile, a significant proportion of engineering students are also struggling to master basic calculation methods. This discrepancy can be resolved by reformulating the goals of mathematics education and applying new approaches and methodological tools. It must be recognised that while a large part of the theory that forms the backbone of classical mathematics education in engineering is not encountered by engineers in the course of their careers, they should have a working knowledge of some of the methods of applied mathematics. [2]

Professors of engineering are calling for a transformation in the teaching of engineering mathematics. László Tóth, a former professor of mechanics at the University of Debrecen, has stressed in several lectures that "Mathematics should be given to engineering students as a tool." Today, there is a wealth of mathematical software available, so that in practice, a multitude of problems can be solved if we know how to use the tools. For a long time, without an appropriate tool, mathematics was only an elegant background for engineering work, calculations were practically infeasible in daily work, decisions were typically based on engineering estimates, practice and experience in the field.

The numerical (and sometimes symbolic, analytical) methods built into software now allow 'exact' calculations, with great economic benefits. Here we need to go into the meaning of 'accuracy'. Although symbolic (analytical) calculations do indeed provide an accurate answer to mathematical problems that can be solved, in many cases, when studying real systems, the only way to arrive at a solvable problem is to make significant neglections and create simplified models. Thus, even if the solution is accurate in some sense, it is only an approximate solution to the original technical problem, and it is often not even possible to check how much the deviation from the exact solution is. Numerical methods are declared to give only an approximate solution, but the 'error' can usually be reduced arbitrarily by using a more detailed model, which of course usually leads to a drastic increase in computation time.

Engineering mathematics education has to face the fact that "In the future, many more engineers will need to know mathematics that few people understand in depth", as Péter Korondi, professor of mechatronics at the University of Debrecen, has emphasised in several lectures. The masses cannot be expected to understand abstract mathematics, but it is essential that mathematics is available as a tool for engineers, at least for those who do development work. And as we live in an age of smart devices, where the built-in knowledge gives the product its utility, more and more people are becoming developers at some level.

3.2. Effective mathematics education in engineering education

The essential elements of our approach are:

- formulating the desired competences;
- structuring the mathematics curriculum on the basis of competences;
- defining and measuring efficiency;
- formulating cross-curricular projects and publishing them (mainly) as homework;
- refreshing the mathematical knowledge required for the professional courses in the context of technical problems, project-based learning of mathematics in professional courses;
- preparing specific maths workbooks to support learning and relearning maths which help independent learning as well.

For example, understanding computations in discrete-time system models can be formulated as a competence.

In this case, the competence-based structuring of the curriculum means a pair-wise discussion of derivation and numerical derivation.

And the effectiveness of teaching is measured by students' ability to recognise and perform the necessary calculations when solving technical problems.

Cross-curricular homework assignments help students to understand the connections between mathematical and technical concepts and to apply the methods they have learned.

A good understanding of the use of mathematical software (in particular Matlab) as an everyday tool (calculator and engineering development environment) should be introduced at the beginning of the course in the mathematics courses.

3.3. Project-based learning of mathematics in the context of technical diagnostics

In many cases, students' mathematical knowledge is already well lost when learning specialised professional subjects, and, on the other hand, the specific needs of applications are not even brought up when learning mathematics. While the teaching of mathematics should aim to cover a wide range of applications, this cannot be done for every single application, partly because of the limited time available and partly because some applications only affect a small group of students by specialisation.

In the mechanical engineering training under review in this article, there is a gap of at least two years between the study of mathematics and its application in diagnostics. This raises not only the question of what needs to be learned (as a new material) in the context of diagnostics, but also what needs to be relearned in mathematics. [2]

The theoretical part of vibration diagnostics (**Figure 1.**) which is the main part of the diagnostics course, includes signal processing (applied mathematics). Thus, the learning and relearning of the related mathematics can be linked to a professional project. In this way, we can both highlight the usefulness of previously learned knowledge and motivate students to acquire new knowledge.

Main topics in vibration diagnostics:

- harmonic vibrations (amplitude, period, frequency, phase);
- displacement, velocity, acceleration, superposition;
- symptoms in the time domain;
- symptoms in the frequency domain (**Figure 2**);
- complex investigations in time-frequency domain, shock pulse method (**Figure 3**);
- signal conditioning.

Closely related topics in math:

- sine and cosine functions (range, period, sign, zeros);
- basic function transformations;
- differential and integral calculus;
- basic statistics;
- Fourier theory;
- wavelet transform, multiresolution analysis;
- filters.

A typical project that can be used as a framework for learning mathematics: condition assessment of a drive (electric motor, gearbox) (**Figure 4**). Steps:

1. Planning
   - identification of measuring points;
   - selection of measurement techniques for each measuring point;
   - provide the data needed to apply the measurement techniques;
   - add the desired evaluation methods to the measurement plan, set the required measurement parameters.
2. Measurement
3. Assessment of the condition of the machinery components inspected on the basis of the measurement results

Figure 1. *Laboratory measurement: test bench and measuring system.*

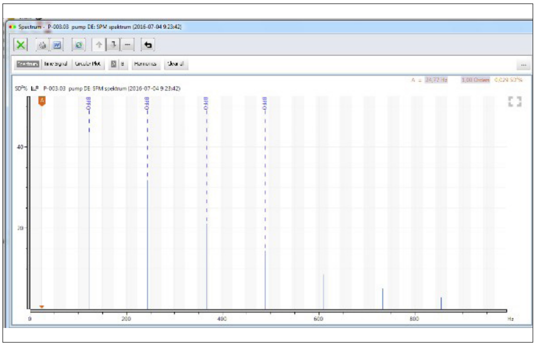

Figure 2. *A symptom in the spectrum* [4]

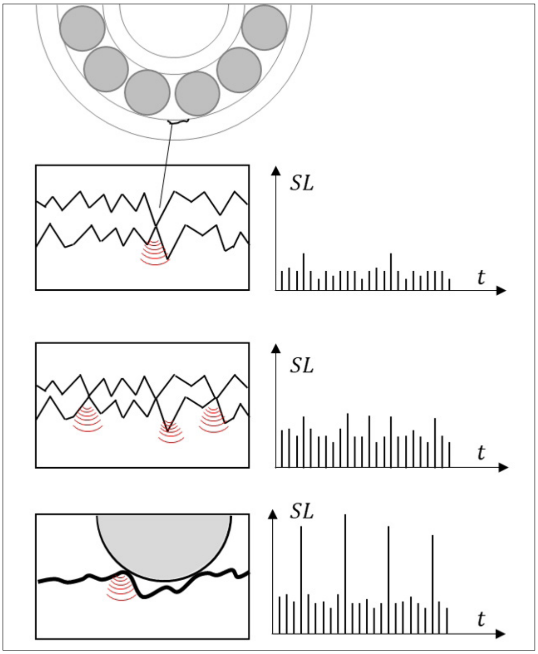

Figure 3. *Bearing testing by shock pulse method* [4]

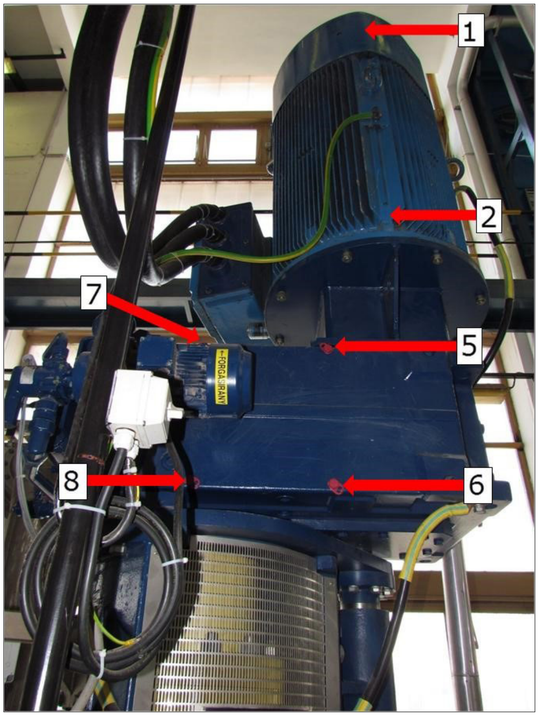

Figure 4. *Operational measurement: testing bearings in a drive train.*

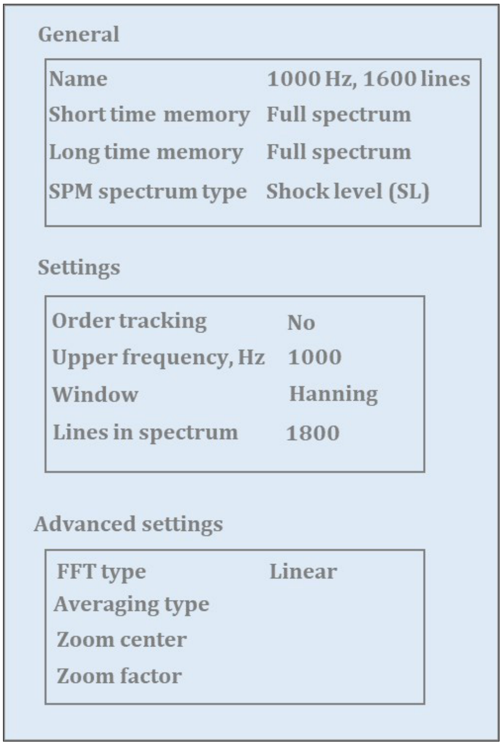

Figure 5. *Setting spectrum parameters.* [4]

Table 1. *Related diagnostic and mathematical tools in the project:*

Diagnostics	Mathematics
skewness, kurtosis, crest factor (peak/RMS)	descriptive statistics, relative frequency histogram
frequency spectrum, frequency range, number of lines in the spectrum, windowing	Fourier series, Fourier coefficients, Fourier transform, discrete Fourier transform, FFT, window functions
shock pulse method, bearing diagnostics, gear diagnostics, electric motor faults	complex investigations in time-frequency domain, wavelet transform, multiresolution analysis, scalogram

4. Conclusions

The ever-accelerating development of engineering is a challenge for those who want to keep up with change.

In a few decades, the effective ways of acquiring knowledge have changed completely, and the viability of traditional engineering education, in which teaching methodology issues were hardly ever raised, is weakening. This is borne out by the general opinion among young people that learning 'from the internet' is much more effective. If we look at the reasons for the popularity of online professional courses or trainings, we soon realise that one of the fundamental difference is the thoughtful way in which the knowledge is delivered (assuming, of course, that both contents are professionally correct).

Institutionalised education must also keep pace with the development of methodological tools, and focus on effectiveness, i.e. the retention of knowledge that is necessary for engineering work. Nothing is more indicative of the effectiveness of teaching a subject than the ability to apply it to other subjects or to practical engineering work.

The role of mathematics in education has changed even more, as technological tools make mathematics, at least some parts of it, more usable, even indispensable. Thus, it is becoming less and less a self-serving subject, and the learning of mathematics must be integrated into professional subjects through the coordination of topics, joint projects, homework and specific (application-oriented) mathematics teaching materials.

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