Undergraduate Engineering Students' Conceptual and Procedural Knowledge of Wave Phenomena

Original Scientific Paper

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Abstract *– The engineering students' education at the university level is mainly focused on procedural knowledge which includes proficiency in problem-solving and calculation whereas their conceptual knowledge, as another very important factor associated with the enhancement of engineering skills, is often insufficient. The aim of this study is to assess the undergraduate engineering students' conceptual and procedural knowledge of wave phenomena as one of basic topics in introductory physics courses either in high school or college as well as in electronic courses at the graduate level of electrical engineering. This paper also examines the change of engineering students' conceptual understanding in this domain prior to and after instruction in the calculus-based physics course (Physics 2) and the relation between students' conceptual and procedural knowledge of wave phenomena. The undergraduate engineering students' procedural knowledge was measured by assessing their performance in the final exam in the calculus-based physics course, whereas the modified Wave Concept Inventory (mod-WCI) test was designed as a multiple-choice questions test to assess their conceptual understanding of wave phenomena. The obtained results were compared with the assessment of J. J. Strossmayer University of Osijek engineering students' conceptual understanding of electromagnetism. This assessment has been conducted recently using a well known multiple-choice test, the Conceptual Survey of Electricity and Magnetism (CSEM). The data analysis of multiple-choice questions was performed by statistical methods of classical test theory which determines reliability and discrimination of the test as well as the relation of particular questions to the entire test. Frequency distributions, normalized gain, correlations, and standardized Student's t-test were also used in data analysis. Significant difficulties in the engineering students' conceptual understanding of wave phenomena and some students' misconceptions in this domain have been identified. A rather low correlation between students' conceptual and procedural performance in the research physics domain has been recognized and confirmed.*

Keywords *– conceptual and procedural knowledge, CSEM testmod-WCI test, multiple-choice questions, misconceptions, wave phenomena*

1. INTRODUCTION

The engineering education and training methods have been under constant modifications in the recent period. Among others, these changes are a consequence of the Bologna process which is considered a major revolution in the European Higher Education. The main aim of the Bologna process is to create a common and comparable system of academic standards and quality within Europe. The issues in the area of higher education will have to deal with various challenges like changes in the curriculum, adaptations of teaching/

learning methods, implementation of systems directed at recognition of qualifications (academic and professional), development of global accreditation schemes, provisions for continuous professional development and valuing informal acquisition of competencies and knowledge [1].

Modern engineering courses are aimed at acquisition of competences and skills. As a consequence, graduated engineers are expected to be able to apply knowledge of mathematics, science (physics) and engineering; to design and conduct experiments and to analyze and interpret data; to design a system, component or process to meet the desired needs; to work in multidisciplinary teams; to identify, formulate and solve engineering problems; to understand professional and ethical responsibility and to communicate effectively; to understand the impact of engineering solutions in global and social context; to recognize the need for long-life learning and to get engaged therein; to have knowledge of contemporary issues; to use techniques, skills and modern engineering tools necessary for engineering practice [2]. Thus, engineers need to become reflective thinkers and effective problem solvers.

Several of the aforementioned engineers' educational outcomes overlap with the learning objectives of the calculus-based introductory physics courses. The learning objective of the physics course program is to help students in building good functional understanding of physics and developing problem-solving skills so that they can use what they learn to solve problems in different contexts. This requires students to develop multiple skills such as the ability to understand and use fundamental concepts in physics; to know when and where to apply specific concepts; to express their functional understanding in various types of representations including graphs, diagrams, equations and textual explanations and to understand the nature of physics and its application in everyday situations.

Nowadays, students are expected to be successful in science, technology, engineering and mathematics (STEM). However, recent studies have shown that students, due to lack of sufficient interest, under-preparedness and poor study skills do not choose science, mathematics and engineering courses for their majors. Therefore, there has been a growing interest in engineering education research to study cognitive aspects of learning with emphasis on understanding and measuring engineering students' learning rather than teaching [3,4].

Learning classifications are commonly used as a way of describing different kinds of learning behaviors and characteristics that students need to develop. They provide a useful tool in distinguishing the appropriateness of particular learning outcomes and because of that they are often used to identify different phases of learning development. The most common and earliest of these is Bloom's Taxonomy (1956) which consists of three domains: Cognitive, Affective and Psychomotor. The cognitive domain of the original Bloom's Taxonomy provides six levels of learning: knowledge, comprehension, application, analysis, synthesis and evaluation [5]. A recently revised Bloom's cognitive domain has a hierarchy of categories that capture the process of learning, from remembering information to creating something new: remember, understand, apply, analyze, evaluate, and create. A knowledge dimension has been added to these levels (factual, conceptual, procedural, metacognitive) [6,7].

Many undergraduate courses are taught in the first three or the lower levels of Bloom's Taxonomy whereas engineering education has become more interested in the upper levels of thinking skills.

Successful acquisition of STEM domains contents requires both procedural and conceptual knowledge. However, engineering students' education, at the university level, is mostly focused on the development of procedural knowledge which includes formulating and problem-solving mathematically. By definition, the procedural knowledge, which is considered "knowing how" knowledge, is a dynamic and successful utilization of knowledge, methods, and rules within relevant representation forms. On the other hand, conceptual knowledge is defined as the comprehension of physical concepts, operations and relations in a certain physics domain. Students' knowledge and understanding of facts and methods are organized in a coherent way and they know how to relate the concepts (e.g. force and field) and to apply them in different contexts [8,9]. If learned with understanding, the knowledge of particular connections between concepts, rules and problems expands and becomes more general. In that way, a solved problem can introduce a new concept or rule. The research of conceptual learning in engineering science indicates that understanding of conceptual knowledge is a critical factor for development of competences and expertise in engineering students and practicing professionals [9,10].

Despite numerous researches in engineering education conducted on the development of students' conceptual knowledge, rather little is known about engineering students' procedural knowledge and its interaction with the conceptual knowledge which influences the development of engineering students as reflective thinkers and effective problem solvers. Recent studies have confirmed the interdependent relation between conceptual and procedural knowledge and that interaction is very complex [9,11]. Conceptual knowledge makes learning procedural skills easier and frees cognitive capacity for learning more difficult procedures. When skills are learned without understanding, they are learned as isolated bits of knowledge and it can be difficult to engage students in activities that help them understand the reasons underlying the procedures. On the other hand, without sufficient procedural knowledge, the students have trouble deepening their understanding of basic ideas and solving problems mathematically.

A central component in learning new concepts is prior knowledge that influences the way new information is understood and scientific concepts are learned. In the last twenty-five years, many studies of physics education have established that before taking an introductory physics course students have many preconceived ideas about physical systems in nature. These ideas differ from the accepted scientific ideas and are often called an alternative conception or a misconception. The misconception is a concept or idea that is embraced prior to instruction and is inconsistent with the current scientific concept [12]. Moreover, students' misconceptions have a negative influence on further comprehension of scientific concepts of physical systems. A scientific explanation of physical phenomena often differs from intuitive ideas or existing conceptual structures. Numerous studies have shown that many students lack correct conceptual understanding of science and engineering concepts, even after a successful completion of courses in which these concepts are taught [13,14]. Thus, the effectiveness of introductory physics instruction is important to enhance students' attitudes regarding the understanding of scientific processes, such as the improvement of quantitative problem solving, the improvement of laboratory skills, and the improvement of reasoning skills.

In recent time, the STEM disciplines have increased their use of Concept Inventories (CIs) which are valuable and necessary diagnostic instruments to investigate students' learning in the fields of science and instructional effects at a student, classroom, and/or instructional program level. Unlike typical assessments of student academic achievement, the CIs represent a unique form of multiple-choice assessment tests which tends to be highly focused on a small set of key concepts and understandings within a limited domain of academic content. Thus, the CIs in higher education science can provide a learning opportunity for students and professors alike [15].

Research on students' conceptions in physics increased dramatically after 1985 and a wide array of innovations in physics instruction have subsequently utilized the CIs as independent methods of evaluation [16]. Nowadays, many CIs tests have been developed and applied to assess students' achievement and conceptual understanding of various physics domains in both traditional (lectures) and advanced (interactive) instruction and at different levels of education. These multiple-choice tests include various physical areas such as kinematics (TUG-K test), force and motion (FCI test), DC-circuits (DIRECT test), waves (WCI test), electricity and magnetism (BEMA test, CSEM test) [17-24]. These tests usually contain multiple-choice questions because in that way it is possible to compare various groups of students. In general, science CIs contain between twenty and thirty-five questions. The question, also called an item, consists of both a stem and response options. The stem refers to the statement that precedes the choices, or response options, in a multiple-choice question. Response options are sub-divided further in the correct response and the incorrect response options. The incorrect response options are often called distracters (or incorrect answers). The design of the CIs goes to conceptualizing the nature of the situations to be presented and developing plausible distracters that represent a range of partially correct understandings to fully incorrect understandings and misconceptions.

The CIs test can be used as both a pretest and posttest. A pretest is often administered at the beginning of a course, whereas a posttest can be given at the end of a course. In that way, it is possible to assess the students' initial conceptual knowledge of various physics domains and the effects of various teaching techniques, methods and approaches on students' knowledge and understanding in order to compare courses, curricula and instructional methods.

Wave phenomena and electromagnetism were chosen in this study as domains to evaluate the engineering students' overall knowledge since these represent basic topics of physics curricula at all levels of education: primary, secondary and university. However, electrical engineering theories and principles are based on understanding of these domains. Nowadays, wave propagation and signal processing are important in engineering. There are many technical and industrial applications that require knowledge of these topics; first of all, wireless communication and antenna and microwave technology.

Students' learning of wave phenomena begins with basic knowledge from introductory physics courses and builds up to the graduate level of electrical engineering courses. Wave concepts play a critical role in learning topics such as mechanical and electromagnetic waves, sound, physical optics and quantum mechanics. Students discover the wave character of particles such as electrons, photons, etc. Electrical engineering courses build upon basic wave concepts in order to understand analytical models that describe waves, their propagation and their interactions. For example, students learn Maxwell's equations and their application to the propagation of electromagnetic waves. These domains are often viewed as being the most abstract and conceptually difficult ones in electrical engineering education. Physics education research has shown that students have difficulties in understanding wave and electromagnetic phenomena because of the abstract nature of these subjects which are difficult to visualize and because of the very complex mathematical formalism [25-27]. That formalism includes e.g. vector algebra and differential and integral calculus. Furthermore, students' mathematical skills have not been developed enough, which makes it difficult for them to acquire the aforementioned physical contents. The study conducted among engineering students revealed that the ability in mathematics was found to be the best single predictor of engineering success [28].

This study presents the evaluation of conceptual and procedural knowledge of wave phenomena and electromagnetism conducted among undergraduate students of electrical and computer engineering at the Faculty of Electrical Engineering, J. J. Strossmayer University of Osijek (FEE UNIOS). The concept test about oscillations and wave phenomena, called the modified Wave Concept Inventory (mod-WCI) test, was designed as a diagnostic tool for assessing students' conceptual knowledge. The mod-WCI test is partially based on an American assessment instrument, the Wave Concept Inventory (WCI) test, which was developed to measure cognitive development of electrical engineering students in the area of wave phenomena [22]. It was administered as both a pretest and a posttest for undergraduate engineering students enrolled in the calculus-based physics (Physics 2) course. The final Physics 2 exam was used to assess students' procedural knowledge of wave phenomena.

One of the most common tests in the Physics Education Research (PER) community is the Conceptual Survey of Electricity and Magnetism (CSEM) [13]. The CSEM is designed to assess students' conceptual knowledge of electricity and magnetism including mathematical formalism in explaining electromagnetic phenomena. A detailed investigation of the application the CSEM test among engineering students at J. J. Strossmayer University of Osijek was presented in the previous paper [29]. In this paper, for the purpose of comparison, only the results from undergraduate electrical and computer engineering students at FEE UNIOS are discussed due to assessment of engineering students' conceptual knowledge using the CSEM and mod-WCI tests.

Possible correlations between students' conceptual and procedural knowledge of wave phenomena and electromagnetism have also been investigated.

2. BACKGROUND OF THE SAMPLE

The study was conducted at the end of the first (winter) and second (summer) semester in academic year 2010/2011 and it involved 169 first- year undergraduate engineering students at the Faculty of Electrical Engineering (FEE), Josip Juraj Strossmayer University of Osijek.

The students were classified into two groups:

- electrical engineering (FEE-EE, 68 students)
- computer engineering (FEE-CE, 101 students)

After a successful completion of the undergraduate study programme, the students are awarded a bachelor degree in electrical and computer engineering. Prior to testing, the undergraduate students at the Faculty of Electrical Engineering finish two semesters of calculus-based general physics courses (Physics 1, Physics 2) and mathematical courses (Calculus 1, Calculus 2), which include linear algebra, differential and integral calculus. In addition, they have also been instructed in Fundamentals of Electrical Engineering (FofEE1) as one of the engineering courses. The aim of the Fundamentals of Electrical Engineering 1 course is to teach the basic laws in electrostatics and electrodynamics and to apply these concepts to solving various field problems. In particular, this engineering course includes properties of electrical and magnetic fields and electrostatic potential, static currents, capacitance, inductance and conductance. The main objectives of these introductory calculus-based physics courses are to clearly and logically present the basic concepts and principles of physics and to strengthen students' understanding of concepts and principles through a broad range of applications in the real world. During the first semester, the students are instructed in calculus-based general physics (Physics 1) which covers mechanics and heat and thermodynamics. Students acquire knowledge of elementary classical physical concepts and mathematically formulated laws of mechanics and thermodynamics, which enables them to understand physical phenomena in nature and technology as well as to solve simple problems. In the second semester, they attended a calculus-based general physics course (Physics 2), which covers wave, electromagnetic and optics phenomena. In detail, the course in Physics 2 includes oscillations and wave motion, Maxwell's equations of electricity and magnetism, electromagnetic waves, the nature of light and the laws of geometric optics and the concepts of modern physics such as particle properties of waves, wave properties of particles, models of atom, the hydrogen atom, atomic structure and spectra. The course Physics 2 is focused on explaining wave, electromagnetic and optics phenomena and quantitative problem solving and on the application of skills to solving basic engineering problems. The associated mathematical formalism includes complex numbers, linear algebra, linear systems of equations, the basics of differential equations, differential and integral calculus of vector-valued functions, vector field and curvilinear coordinates.

The physics courses consisted of lectures, seminars (problem-solving exercises), homework, laboratory exercises, and a final exam. Students could have participated in seminars, where they solved standard textbook problems with the help of a teaching assistant. Besides, obligatory homework was assigned and homework tasks and problems were more complex and demanding than those in seminars. Croatian language textbook [30] and exercise book [31] about waves and optics were used during the Physics 2 course.

The analysis of the types of secondary schools students had completed before enrolling in university has shown that 51% of the undergraduate students at the Faculty of Electrical Engineering had finished grammar school (19% natural sciences grammar school, 32% other grammar schools). The rest of the students, i.e. 49%, had completed vocational schools (most of them electrical engineering schools). The analysis of students' achievements in Physics and Mathematics in secondary schools has shown that, on average, the FEE-EE and FEE-CE students were very successful; i.e. 23.8%, 35.0%, 34.4% and 6.8% of them had had grade A (excellent), B (very good), C (good), and D(sufficient), respectively.

Gender distribution shows that the sample consisted of 92% male and 8% female students studying at the Faculty of Electrical Engineering, University in Osijek.

3. ASSESSING DIAGNOSTIC INSTRUMENTS

The conceptual and procedural performance of students prior and after instruction in the Physics 2 course was evaluated by two separate tests; i.e. a concept test and a final exam.

Conceptual knowledge was assessed by two assessing diagnostic tools: the Conceptual Survey of Electricity and Magnetism (CSEM) test [24] and the modified Wave Concept Inventory (mod-WCI) test. In winter semester, the CSEM was administered as a posttest to both groups of students at the FEE UNIOS in the last week of the first semester, after the students had completed engineering (FofEE1) and calculus-based physics (Physics 1) courses. In summer semester, the mod-WCI test was administered as a pretest, before (in the first week of the semester) and, as a posttest, at the end (the last week of the semester) of the calculus-based physics (Physics 2) course to both groups of students.

Before the test, the researcher explained the purpose and the importance of such testing. In addition, the students were asked to fill in the form supplying the information on gender, secondary school education and their prior achievements in physics and mathematics in terms of grade in the respective subject. Although the testing was anonymous, each student was assigned a code that enabled them to check their results. As a motivation, points were earned and the results were taken into account when assessing their achievement in the calculus-based physics courses or in the FofEE1 course.

The final exam of the Physics 2 course consisted of five problem-solving exercises which can be found in various textbooks and tutorials. Problem-solving exercises were chosen to assess students' procedural knowledge and they were similar to complex homework exercises and standard textbook problems which had been solved during seminars. Exam tasks required much less work, since they needed to be completed in a limited period of time. Although the purpose of problem-solving exercises was to assess students' procedural knowledge, they clearly included elements of conceptual knowledge as well. In order to understand definitions and principles and to select adequate mathematical methods students had to show conceptual understanding. However, the main task in problem-solving exercises was to choose the appropriate mathematical formula, use it properly, compute each step, establish possible relations, and arrive at a solution. All these steps required procedural knowledge and therefore it could have been expected that problem-solving exercises would assess students' procedural understanding relatively well in the context of researched physics domains.

The mod-WCI and the CSEM test scores and the final exam performance scores were analyzed statistically.

3.1. MODIFIED WAVE CONCEPT INVENTORY (mod-WCI) TEST

In this study, conceptual learning gains among undergraduate engineering students were assessed by using the conceptual test about oscillations and wave phenomena - the modified Wave Concept Inventory (mod-WCI) test. This mod-WCI test is based on an American assessment instrument, the Wave Concepts Inventory (WCI) which has been developed to assess students' conceptual understanding of wave phenomena that begins with basic knowledge in physics and builds up to the graduate level of electrical engineering [21,22]. The WCI is an assessment tool which covers several areas of wave phenomena concepts including visualization of waves, mathematical description of waves and wave definitions. It is a multiple-choice test, which is different from other concept inventories, because it allows more than one correct answer to some questions. It consists of twenty multiple-choice questions with possible thirty-four correct answers. The use of multiple correct answers is unique to this concept inventory. In fact, choosing more than one correct answer correlates with increased understanding of concepts within some domain of academic content. Increased conceptual understanding means that a student performs at a higher level of learning by the Cognitive domain of learning proposed by Bloom's Taxonomy of Educational Objectives [5]. The questions in the original WCI test range from the lowest level of Bloom's Taxonomy, Knowledge, to Analysis, which is the fourth level. Fig. 1 illustrates a sample question (question 5) in the original WCI test.

(5) Suppose two different sound waves encounter each other - they meet at the same location in space at the same time. What happens?

(a) They scatter from each other and move in divergent directions.
(b) Their amplitudes add together.
(c) Their displacements add together.
(d) Their phases add together.

Fig. 1. The example of the original WCI item (question 5)

For example, in question 5 in the WCI test, many students will immediately recognize (b) as the obvious answer and therefore, it is the first level of learning, knowledge. However, students with more experience will notice that (c) is a correct answer because it is a generalization of answer (b). This answer shows the second level of learning, comprehension. One of the choices should be obvious to students with basic understanding of a particular concept, but students with deeper understanding of a particular concept should be able to recognize more correct answers. Nevertheless, students choosing the higher level answer before the lower level answer are not likely to understand the concept at a higher level. In other words, students may be guessing.

Table 1. Conceptual areas and question numbers addressing each area of the mod-WCI test

Conceptual area	Question number from [32,33]	Question number from the Wave Concept Inventory (WCI) Survey[21,22]
Oscillations	**1–8, 14** (1-MRQ, 8- MCQ)	
Wave phenomena	**12, 13, 15, 16, 18, 19, 20, 22** (2-MRQ, 6-MCQ)	**9, 10, 11, 17, 21, 23–30** (8-MRQ, 5-MCQ)

The mod-WCI test as an assessment instrument in this study covers a wide-ranging area of waves. It consists of questions including oscillatory and wave motions, a mathematical description of wave motion and wave equation, wave pulse and superposition of waves. Besides, it includes the question about wave optics phenomena (refraction of light, diffraction and polarization of light). When designing the mod-WCI test the questions from the original WCI test were used (the total of 13 questions) [21,22], as well as the examples of conceptual physics tests from the textbook by Eric Mazur "*Peer Instruction – A User's Manual – Concepts test*" and other sources (the total of 17 questions) [32,33]. The mod-WCI test contains thirty multiple choice questions, whereby 11 questions are multiple response questions (MRQ) (questions with many correct answers) and 19 questions are multiple choice questions (MCQ) (with only one correct answer). The structure of the mod-WCI test is given in Table 1.

3.2. CONCEPTUAL SURVEY OF ELECTRICITY AND MAGNETISM (CSEM) TEST

Undergraduate engineering students' conceptual knowledge of electricity and magnetism was measured by using the Conceptual Survey of Electricity and Magnetism (CSEM) concept test [24]. The CSEM test is a well-known diagnostic instrument used to assess students' knowledge of electricity and magnetism including mathematical formalism in explaining the electromagnetic phenomena and to diagnose and identify difficulties they have in this domain.

The CSEM consists of 32 multiple-choice questions which are quite unequally divided by the authors into 11 conceptual areas. Some areas contain only a few questions, whereas some questions cover several conceptual areas. This distribution of questions makes it more difficult to analyze test results. However, 11 conceptual areas can be rearranged into six larger ones each of which containing the same number of questions [34]. Conceptual areas of the CSEM are: the electric charge and force; the electric field and force; the electric potential and energy; the magnetic field and force; the electromagnetic induction; Newton's laws in an electromagnetic context. A sample question (question 28) is shown in Figure 2.

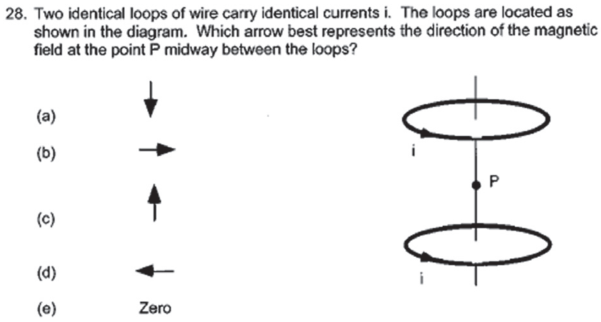

Fig. 2. The example of the CSEM item (question 28)

The results of the undergraduate engineering students' conceptual knowledge of wave phenomena at the FEE UNIOS were compared with the results of a similar study carried out with the undergraduate students at the Faculty of Science, University of Zagreb (FS UNIZG) [33]. At FS UNIZG, the assessment of conceptual understanding using the same mod-WCI test was administered to 76 second-year students (48 research oriented study students and 28 educational studies students) who had completed two semesters of calculus-based introductory physics courses. First-year introductory physics courses included both mechanics and electromagnetism. At FS UNIZG, the mod-WCI test was administered as a pretest, i.e. before the calculus-based physics course which includes oscillation and wave phenomena. Besides, the results of the applied CIs tests have also been compared with the published results of the American study and with previously conducted testing at FS UNIZG [24,29,33].

4. STATISTICAL ANALYSIS OF THE CIs DATA

Traditional multiple-choice concept inventories (CIs) in physics education are typically designed to assess students' critical conceptual understanding of different topics and also to reveal students' misconceptions in different physics areas. Over the years, CIs have been used mainly to look at the overall test scores and average learning gains. Thereby, students' concept inventories test scores are often used as the measure of students' conceptual understanding of physics topics. However, recent research has introduced new ways of analyzing CIs [35]. Studies indicate that for any assessment instrument it is important to analyze and monitor the functioning of the CIs test. Besides, it is important to realize that the meaning of the overall students' test scores depends strongly on the structure and functioning of the test as a whole, as well as on the functioning of each question (item). Thus, the obtained mod-WCI and CSEM data were analyzed using classical test theory as one of statistical methods for analyzing multiple-choice questions. It assumes that the total score was made up of two components; i.e. a true score and a random error. The aim of statistical analysis is to examine the reliability and the discrimination of applied CIs tests. For a reliable test, similar outcomes are expected if the test is administered twice (at different times), assuming the examinees' performance is stable and the testing conditions are the same. For the discriminatory test, the results can be used to clearly distinguish those who have a robust knowledge of the tested material from those who do not. In this way, the problematic questions can be identified.

Classical test theory provides different measures to evaluate multiple-choice tests and their items. Five measures used in this study are often used in science education research [35]. Three measures were used for *item analysis*: item difficulty indices (p, q), discrimination index (D), point biserial coefficient (r_{pbc}), and two for *test analysis*: Kuder-Richardson reliability index (r_{test}), and Ferguson's delta (δ). This study gives only a brief outline of the meaning of these measures. More detailed information about these measures can be found in Ding and Beichner [35].

The item difficulty index is a measure of the difficulty of a single test item. It is calculated by taking the ratio of the number of correct (p) or wrong (q) responses on the item to the total number of students taking the test. The range for the difficulty index p value is [0,1], but the accepted values are $0.3 \leq p \leq 0.9$. However, it is more appropriate to subtract 0.5 $(q^* = q - 0.5)$ from the difficulty index of each item, so that a medium difficulty is represented by zero. The positive difficulty indicates more difficult items, whereas negative values indicate less difficult items. In this way, the re-scaled difficulties (q^*) can be obtained. The range of the re-scaled difficulty index is $-0.5 \leq q^* \leq 0.5$ [34]. The item discrimination index (D) is a measure of discriminatory power of each item in the test. It is used to differentiate between high-achieving and low-achieving students. A possible range for the item discrimination index D is [-1,1]. Generally, an item is considered to provide good discrimination if $D \geq 0.3$. The point biserial coefficient (r_{pbc}), sometimes referred to as the reliability index for each item, is a measure of consistency of a single test item with the whole test. It reflects the correlation between students' scores on an individual item and their scores on the entire test. The point biserial coefficient has a possible range of [-1,1]. If an item is highly positively correlated with the whole test, then the students with high total scores are more likely to answer the item correctly than the students with low total scores. On the other hand, a negative value indicates that the students with low overall scores were likely to get a particular item correct which indicates that the particular test item is probably defective. Therefore, a widely adopted criterion for measuring "consistency" of a test item is $r_{pbc} \geq 0.2$. If the values of the point biserial coefficient are $0.20 \leq r_{pbc} \leq 0.39$, the item is good, it is very good if $0.40 \leq r_{pbc} \leq 0.59$, and if $r_{pbc} \geq 0.6$ it is an excellent item.

Kuder-Richardson reliability index is a measure of internal consistency of a whole test when test items are dichotomous (i.e., correct or incorrect answers) as in the applied CIs tests. Higher correlations between individual items result in a higher Kuder-Richardson index, indicating a higher reliability of the whole test. The range of the possible values for the KR-20 reliability index is [0,1] [37]. A widely used criterion for a reliable group measurement is $r_{test} \geq 0.7$ and tests with $r_{test} \geq 0.8$ are reliable for individual measurement. In physics education, evaluation instruments are designed to be used to measure a large group of students, so if a certain physics test has a reliability index higher than 0.7, no one can safely claim it is a reliable test [36,37].

Ferguson's delta (δ) is a measure of the discriminatory power of a test. It takes into account how broadly students' total scores are distributed over a possible range. Generally, the broader the total score distribution, the better discriminatory power of the test [23]. A possible range of Ferguson's delta values is [0,1]. If the test has Ferguson's delta $\delta \geq 0.9$, it is considered to offer good discrimination.

For both assessed undergraduate engineering student groups, the overall statistical analysis results of the mod-WCI and CSEM test are shown in Table 2.

5. RESULTS AND DISCUSSION

The results of statistical test analysis of the applied CIs tests summarized in Table 2 indicate that the CSEM administered as a posttest is the adequate diagnostic instrument to assess conceptual understanding of electromagnetism of the undergraduate engineering students at FEE UNIOS. Reliability and discrimination power of the CSEM as a posttest was confirmed by the acceptable average parameters values; i.e. $r_{test} = 0.80$, $\delta=0.93$. The calculated values of the r_{test} reliability parameters for both tested groups of students are higher than the limit value ($r_{test} \geq 0.7$) and quite similar to the results of the posttest administered to American students $((r_{test})_{USA} \approx 0.75)$ [24,29].

The results of statistical analysis of the mod-WCI test revealed that it is not a reliable diagnostic tool, either as a pretest or a posttest, for assessing conceptual knowledge of FEE-CE students because the KR-20 reliability index is too low $((r_{test})_{FEE\text{-}CE} = 0.75)$. For FEE-EE students, the obtained KR-20 index is close to the bottom limit value $((r_{test})_{FEE\text{-}EE} = 0.65)$, and this test could be considered reliable.

Based on the aforementioned, it could be expected that repeated testing under same conditions would give the same results for FEE-EE students. However, for all tested engineering students, the CIs applied as both a pretest and a posttest have good discrimination power because δ–Ferguson parameters have acceptable average values ($\delta_{FEE\text{-}EE} = 0.94$, $\delta_{FEE\text{-}CE} = 0.90$), which indicates that students' total scores are broadly distributed over the classes set in advance (Figure 3.)

Table 2. The overall results of statistical analysis of the applied CIs tests

Statistical parameters	A possible range of values	*Accepted values*	FEE - EE			FEE - CE		
			mod-WCI		CSEM posttest **(N=88)**	mod-WCI		CSEM posttest (N=98)
			pretest (N=68)	**posttest** (N=45)		**pretest** (N=94)	**posttest** (N=101)	
r_{test}	[0,1]	≥ 0.7	0.65	0.62	**0.84**	0.38	0.38	**0.75**
δ	[0,1]	≥ 0.9	**0.93**	**0.91**	**0.97**	**0.91**	**0.91**	**0.88**
$\langle r_{pbc} \rangle_{average}$	[-1,1]	≥ 0.2	**0.27**	**0.27**	**0.40**	**0.22**	**0.19**	**0.32**
$\langle p \rangle_{average}$	[0,1]	≥ 0.3	**0.35**	**0.38**	**0.50**	**0.29**	**0.36**	**0.59**
$\langle D \rangle_{average}$	[-1,1]	≥ 0.3	**0.32**	**0.31**	**0.27**	0.22	0.22	0.15

Table 3. Undergraduate engineering students' overall success in the CIs tests applied at the Faculty of Electrical Engineering, J.J. Strossmayer University of Osijek, in academic year 2010/2011

	FEE - EE			FEE - CE		
	mod-WCI		CSEM posttest **(N=88)**	mod-WCI		CSEM posttest (N=98)
	pretest (N=68)	**posttest** (N=45)		**pretest** (N=94)	**posttest** (N=101)	
Average score, %	35.3	38.2	50.5	29.5	36.3	59.3
Median, %	10.0	11.0	50.0	9.0	11.0	62.5
Standard deviation, %	13.1	12.6	19.3	9.1	9.5	10.8
Standard error of the mean, %	1.6	1.9	2.1	0.9	1.0	1.1
Min – max, %	9.4 – 66.7	20.0 – 76.7	12.5 – 87.5	6.7 – 50	13.3 – 73.3	15.6 – 75.0

Table 4. The results of the normalized gain calculation on the mod-WCI test for undergraduate engineering students at the Faculty of Electrical Engineering, J.J. Strossmayer University of Osijek, in academic year 2010/2011

	FEE - EE			FEE - CE		
	mod-WCI		**gain *g***	mod-WCI		**gain *g***
	pretest (N=22)	**posttest** (N=22)		**pretest** (N=74)	**posttest** (N=74)	
Average score, %	30.6	40.8	0.15	26.4	37.9	0.16
Median, %	30.0	36.7	0.14	28.1	36.7	0.13
Standard deviation, %	12.7	12.3	0.12	7.3	8.0	0.10
Standard error of the mean, %	2.7	2.6	0.03	0.9	0.9	0.01
Min – max, %	10.0 – 63.3	20.0 – 76.7	0 – 0.39	6.7 – 37.5	23.3 – 76.7	0 – 0.68

The overall results of the applied CIs tests (mod-WCI and CSEM) for both tested undergraduate engineering student groups at the FEE UNIOS in academic year 2010/2011 are shown in Figure 3 in the form of frequency distribution, i.e. the number of students in certain classes (percentage bins). Statistical information about obtained results (arithmetic mean, median, standard deviation σ, standard error of the mean $SE = \frac{\sigma}{\sqrt{N}}$, minimum and maximum score) are presented in Table 3.

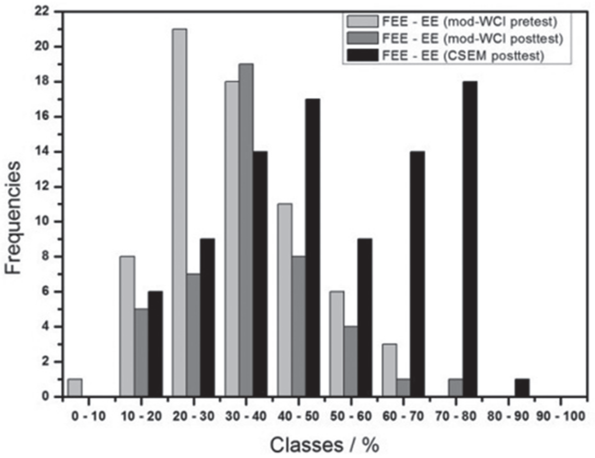

Fig. 3a. Distribution of frequencies for FEE-EE students in the applied CIs

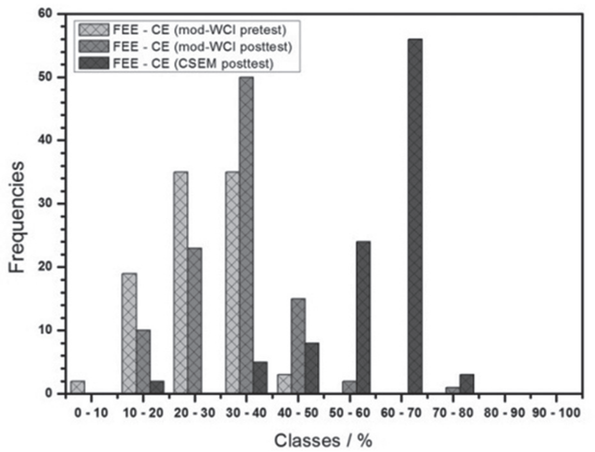

Fig. 3b. Distribution of frequencies for FEE-CE students in the applied CIs

The analysis of the overall results for all tested students shows that both groups have achieved approximately the same results. The average score in the mod-WCI pretest was 32.2%, for both groups of students and 37.2% in the posttest, which is a much lower average score as compared to the results in the CSEM as a posttest (55%). When comparing the CSEM posttest results, the average score of the undergraduate engineering students at FEE UNIOS is slightly better than the score achieved by physics students at the University of Zagreb (48%) and students from American universities (47%) [24,29,33]. However, the average score in the mod-WCI pretest of all tested students was considerably lower than the one scored by physics students from the University of Zagreb (44%) [33].

Frequency distributions for both groups of FEE UNIOS students per class (percentage bin), Figures 3a and 3b, do not follow a normal Gauss distribution (confirmed by applied $\chi 2$-tests). They have also been shifted towards lower classes. In addition, in the mod-WCI frequency histograms for both tested groups significant maxima can be observed in the following classes: 20%-30% and 30%-40%, in both a pretest and a posttest. This confirms that some of the students lack inner (and outer) motivation for such testing. It seems that about 30% of FEE-EE students and 37% of FEE-CE students were guessing randomly when taking the mod-WCI as a pretest. Such results of the pretest were partially expected as students were not familiar with the tested physical domains. Students also lacked a deep understanding of fundamental concepts such as oscillation and waves taught in secondary schools and in the first semester in the university physics courses.

Both groups of students performed slightly better in the posttests, which resulted in the shift of the frequency distribution maximum towards the 30-40% class. In this class, there are 50% of FEE-CE students and 42% of FEE-EE students. It is interesting to note that when comparing the frequency distribution of FEE-CE student' scores in the CIs posttests, more than 50% of students from this group belong to only one class (30-40% for the mod-WCI test and 60-70% for the CSEM test).

The standardized Student's t-test was used to examine whether the correlation between the applied CIs posttest scores for both tested student groups was significant. Figure 4 shows a comparison of the obtained results for both administered CIs as posttests (CSEM vs. mod-WCI).

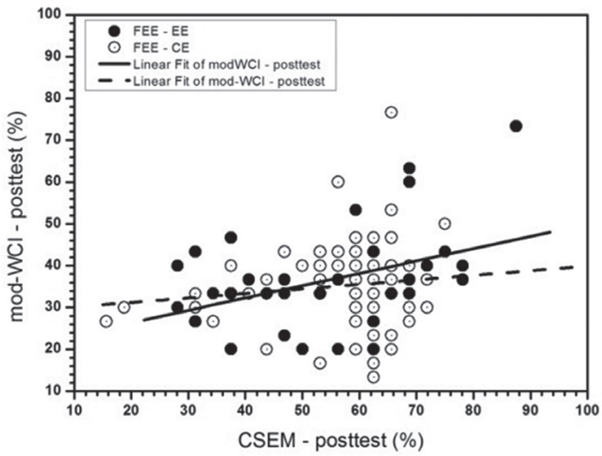

Fig. 4. Mod-WCI posttest scores versus CSEM posttest scores for FEE-EE (solid circle, solid line) students and for FEE-CE (hollow circle, dashed line) students

It can be observed that there is a statistically significant linear correlation at the significance level of 0.05 between these paired values for FEE–EE students (t=2.626; p=0.013; df=33), but not for FEE–CE students (t=1.237; p=0.219; df=93). Based on this positive linear correlation, it can be concluded that FEE-EE students with higher scores in the CSEM test also achieve better scores in the mod-WCI posttest.

5.1. INTERPRETATION OF mod-WCI NORMALIZED GAIN AND PREINSTRUCTION SCORES

Pre- and post-testing is a commonly used method in physics education community for evaluation of students' achievement and/or effectiveness of teaching during a specific period of instruction. A well-known method for the analysis of pre- and post-testing results is the normalized gain which was first introduced to the physics education community by R.R. Hake [38].

The normalized gain, g, is defined as the ratio of the actual gain, G, to the maximum possible gain:

$$g = \frac{G}{100 - S_{pre}} = \frac{S_{post}(\%) - S_{pre}(\%)}{100 - S_{pre}(\%)} \tag{1}$$

where S_{pre} ,S_{post} are the pre- and post-scores and G= S_{post} - S_{pre} is the actual change in the score.

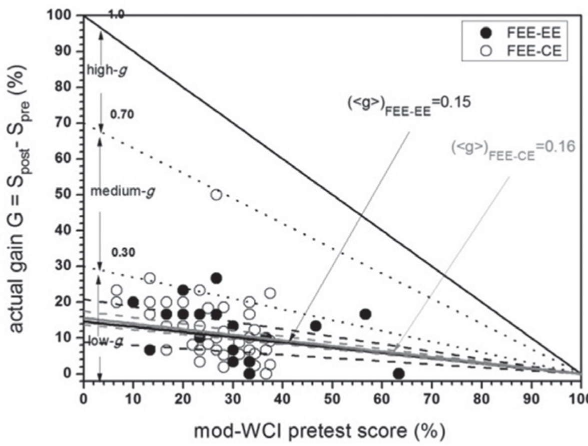

Fig. 5. The Hake's plot for both undergraduate engineering student groups at FEE, J.J. Strossmayer University of Osijek

The three test scores (maximum, pre-test and post-test) can be defined for each student or as an average measure of the group. According to Hake's definition of gain, Eq. (1) holds only if the score of each student is higher on the posttest than on the pretest. The normalized gain is usually expressed by using the appropriate average values: $\langle G\rangle$, $\langle S_{pre}\rangle$, $\langle S_{post}\rangle$. Besides, there are three levels of the normalized gain: "high-g" with $\langle g\rangle \geq 0.7$, "medium-g" with $0.3 \leq \langle g\rangle \leq 0.7$, and "low-g" with $\langle g\rangle < 0.3$.

In this study, for the assessment of effectiveness of the instruction for each tested students group, average normalized gains on the mod-WCI test were calculated by using the Hake`s plot and the results are given in Table 4. Only students who took both a pretest and a posttest (22 – FEE-EE, 74 – FEE-CE) were included in this gain analysis.

Figure 5 shows the Hake`s plot which presents the actual gain G versus the pretest scores S_{pre} for two tested groups of engineering students. The two dotted lines divide the allowed region into areas of high-gain, medium-gain and low-gain. The average normalized gain $\langle g\rangle$ is determined by the absolute values of the slope of the line connecting the point $(\langle S_{pre}\rangle,\langle G\rangle)$ with the point $(100,0)$, where $\langle S_{pre}\rangle$ is the pre-test average score and $\langle G\rangle$ is the average value of the actual gain.

The results show that the scores of almost all students belong to the region of low gain ($\langle g\rangle < 0.3$). Only a few students are in the region of medium gain (Figure 5). These results match Hake's criteria [38] according to which in traditional courses with low interactive engagement the average gain varies generally between 0.15 and 0.30. FEE UNIOS undergraduate engineering students' low gain confirms that traditional teaching methods and strategies dominated over interactive ones.

5.2. IDENTIFICATION OF ENGINEERING STUDENTS' MISCONCEPTIONS ABOUT WAVE PHENOMENA

Figure 6 shows parameters of statistical item analysis of each item (question) in the mod-WCI as a pretest as well as a posttest for two groups of undergraduate engineering students at the FEE UNIOS. The calculated average values of point biserial coefficients for the mod-WCI as both a pretest and a posttest were almost equal $((r_{pbc})_{FEE\text{-}EE} = 0.27), (r_{pbc})_{FEE\text{-}CE} = 0.21))$ and they confirm a good correlation ($r_{pbc} \geq 0.2$) between particular items and the whole test for both tested groups. However, these average values are not as good as those for the CSEM test ($r_{pbc} \geq 0.3$). Average mod-WCI item discrimination indices for both a pretest and a posttest are the same ($\langle D\rangle_{FEE-CE} = 0.22$, $\langle D\rangle_{FEE-CE} = 0.22$) for both groups of tested students. The obtained value for FEE-EE students is at a low level of acceptance, whereas for FEE-CE students it is unacceptable. Almost similar results were obtained for the CSEM test: $\langle D\rangle_{FEE-EE} = 0.27$, $\langle D\rangle_{FEE-CE} = 0.15$. Low item discrimination indices and high values of the re-scaled difficulty indices indicate that the items in the mod-WCI test were too difficult ($\langle q^*\rangle_{pretest} = 0.18$) for FEE UNIOS students. On the other hand, the items in the CSEM as a posttest were much easier because of the low values of their item discrimination indices and low re-scaled difficulty indices ($\langle q^*\rangle_{CSEM} = -0.05$). About 20% of the items for FEE-EE students and over 30% for FEE-CE students in the mod-WCI test both as a pretest and a posttest were too difficult ($q^* \geq 0.4$, above 90% of incorrect answers).

Statistical analysis of the mod-WCI test items revealed some problematic questions and conceptual areas which have been more difficult for the tested engineering students.

All tested students, in both a pretest and a posttest have shown better understanding of concepts relating to oscillation and harmonic oscillator. In the conceptual area which includes oscillatory motion they have had the lowest values of re-scaled difficulty indices, i.e. the students had 40% correct answers. However, it is interesting to note that for FEE-EE students this conceptual area was more difficult in the posttest than in the pretest (about 35% correct answers) (Figure 6a.).

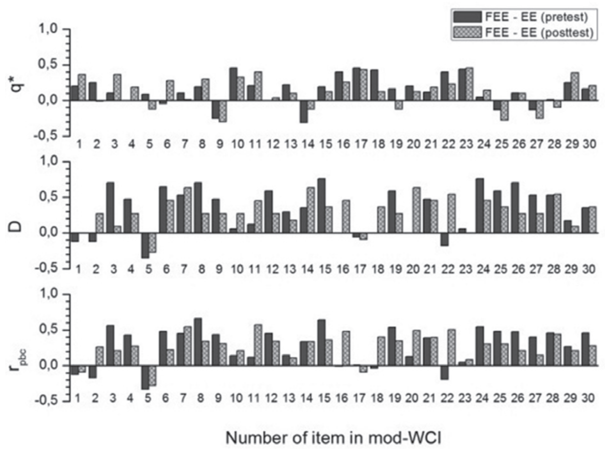

Fig. 6a. Parameters (the re-scaled difficulty index (q*), the item discrimination index (D), the point biserial coefficient (rpbc)) of statistical item analysis of each item in the mod-WCI as a pretest and a posttest for FEE-EE students

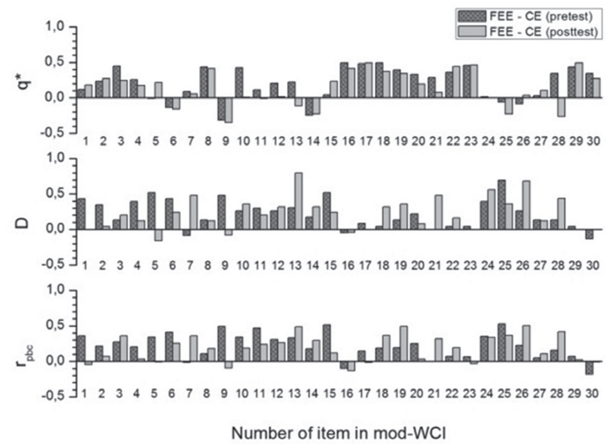

Fig. 6b. Parameters (the re-scaled difficulty index (q^*), the item discrimination index (D), the point biserial coefficient (r_{pbc})) of statistical item analysis of each item in the mod-WCI as a pretest and a posttest for FEE-CE students

Item analysis of the mod-WCI administered as both a pretest and a posttest, indicated that questions 9, 14, 25, 27, 28 ($q^* \leq -0.2$ about 70% of correct answers) were the easiest questions in the test, whereas questions 17, 18, 19, 22 and 23 were by far too difficult ($q^* \geq 0.4$, above 90% of incorrect answers) for both tested groups of students.

The analysis of the easiest questions in the mod-WCI test indicated that the tested engineering students can recognize the wave definition and based on graphical presentation they can recognize the phenomena of the wave' optics such as refraction, diffraction, and polarization of light. Nevertheless, many students seem to make analogy between wave pulse motion and the motion of an object, like a ball [27]. In question 19, a correct answer was expected to show that wave pulses pass through each other. However, the most common answer to this question was that, after a perfectly inelastic collision, the new wave pulse continues to move in the same direction the greater pulse moves (65% of FEE-CE students). This statement is consistent with a description of waves as objects rather than a description of waves as a propagating disturbance within a system. It indicates students' misuse of the concept of collision between two objects. Besides, in question 17, above 60% of the students consider that in the superposition of waves only the wave amplitudes add (question 17) which is in accordance with the first level of learning, knowledge. Only 25% of the tested students consider that wave displacements add together when two different waves meet in the same location at the same time. These correct answers revealed their comprehension as the second level of learning. In general, it could be concluded that students lack a higher level of knowledge of certain concepts.

Furthermore, in this study, the analysis of students' distracters (or incorrect answers) in the mod-WCI test as a posttest has detected a few misconceptions which are often in the domain of wave phenomena such as:

- Both wave length and wave velocity change when the wave frequency changes (52% - FEE-CE, 53% - FEE-EE students)
- When two opposite symmetrical wave pulses which propagate along the string encounter each other, the string remains still. (67% - FEE-CE, 51% - FEE-EE students)
- In a standing wave, the instantaneous velocity of the points along the string equals zero (82% - FEE-CE, 53% - FEE-EE students).

5.3. COMPARISON OF UNDERGRADUATE ENGINEERING STUDENTS' CONCEPTUAL AND PROCEDURAL KNOWLEDGE

FEE-UNIOS undergraduate engineering students' procedural knowledge of wave phenomena was evaluated by assessing their performance in the final exam of the calculus-based physics course (Physics 2). The final exam consisted of five problem-solving exercises similar to homework exercises. Numerical problem-solving exercises included oscillation and wave motion, Maxwell's equations and their application to the propagation of electromagnetic waves, the laws of geometric and wave optics, blackbody radiation and the photoelectric effect. The associated mathematical formalism included linear algebra, linear systems of equations, the basics of differential and integral calculus of scalar-valued and vector-valued functions. The conceptual knowledge was measured by using the applied CIs (mod-WCI and CSEM) test as posttests.

Statistical information about overall scores of the applied CIs posttests for FEE-UNIOS students is given in Table 3. The average score in the Physics 2 final exam was 37.7%±7.7% (standard error of the mean 1.3%, median 39%) for FEE-EE students, and 29.9%±5.5% (standard error of the mean 0.6%, median 26%) for FEE-CE students. A rather low score in the final exam for all tested students is first of all a consequence of difficulties students have with the required mathematical formalism. Although students are mostly able to use appropriate formulae and equations, their mathematical skills are insufficient and questionable.

The relation between conceptual and procedural knowledge was evaluated by using the standardized Student's t-test.

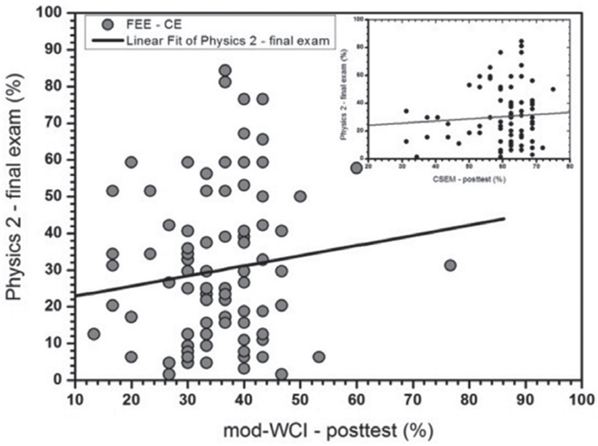

Fig. 7. Comparison of the applied CIs posttest scores with the scores of FEE-CE students achieved in the Physics 2 final exam.

For FEE-CE students, by applying the Student`s t-test, the following parameters were calculated: t=1.193; p=0.236; df=86 for empirical pairs of values (the mod-WCI posttest scores vs. the scores in the Physics 2 final exam) and t=0.764; p=0.447; df=83 for pairs of values (the CSEM posttest scores vs. the scores in the Physics 2 final exam) (Figure 7). These results indicate that there is no statistically significant linear correlation at significance level of 0.05 between scores obtained in the applied CIs tests (mod-WCI and CSEM) as a posttests as compared to procedural performance (final exam in Physics 2) for FEE – CE students.

For the total of 33 pair values from Figure 8a, the Pearson correlation coefficient between conceptual (measured by the mod-WCI test) and procedural performance (the Physics 2 final exam) was r=0.46 for FEE-EE students. This value is positive and statistically significant at significance level of 0.05, which is shown by the test with Kendall's variable ($t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} = 2.883$; p=0.0071; df=31). Furthermore, for the same group of students (FEE – EE), there is no statistically significant linear correlation between conceptual understanding of electromagnetic phenomena measured by the CSEM test and procedural knowledge of physical phenomena measured in the Physics 2 final exam (t=1.039; p=0.307; df=8) (Figure 8b).

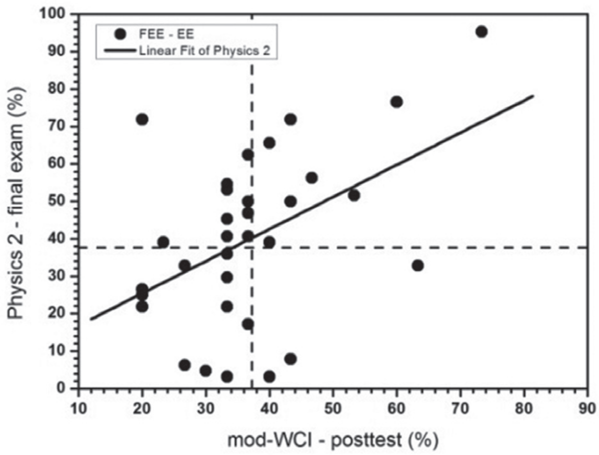

Fig. 8a. Comparison of the mod-WCI posttest scores with the scores of FEE-EE students in the Physics 2 final exam.

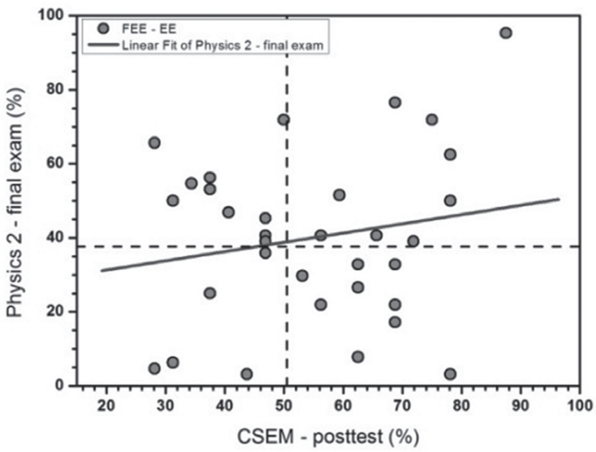

Fig. 8b. Comparison of the CSEM posttest scores with the scores of FEE-EE students in the Physics 2 final exam.

The absence of the correlation between procedural knowledge measured in the Physics 2 final exam and conceptual knowledge measured by the CSEM test indicates that students' conceptual knowledge of electromagnetism has not improved their procedural knowledge. Obviously, in the Physics 2 course many engineering students have had problems with the required mathematical formalism regardless of their conceptual knowledge of electricity and magnetism.

The results have indicated that only for FEE-EE students a rather low positive and statistically significant correlation between conceptual and procedural knowledge of wave phenomena has been established. Thus, for a detailed comparison of conceptual and procedural performance of FEE-EE students scatter plots have been made for the data. The graph area has been divided into four quadrants (numbered counter-clockwise starting with the top right quadrant). The vertical and horizontal axes have been split at the corresponding median value of the applied CIs tests as a posttest and the Physics 2 final exam for FEE-EE students (Figure 8).

In Figure 8a, the majority of students (36% of FEE-EE students) have neither conceptual knowledge nor procedural knowledge (3rd quadrant), whereas 30% of students lack conceptual knowledge but have sufficient procedural knowledge (2nd quadrant). The first quadrant in Figure 8a contains students (24% of FEE-EE students) who performed well both conceptually and procedurally, while the fourth quadrant contains students (9% of FEE-EE students) performing well conceptually, but not procedurally.

The results indicate that in the context of wave phenomena, it is possible to have considerable procedural skills without conceptual knowledge but a reverse situation is also possible. Because students' exam preparation has been characterized by memorizing equations and formulas, many students have been able to apply the appropriate formula, but they lack understanding of the basic principles. In that case, the success depends on whether students remember the correct formula for the problem and calculate it correctly.

The present study supports a dynamic interaction approach which considers conceptual knowledge as necessary, but not sufficient for a correct use of a procedure [11,39]. The obtained results suggest that some general knowledge of the basic concepts and relations is needed in order to successfully solve problem exercises. Conceptual knowledge forms the basis for learning new procedures, but once acquired, the procedures develop independently.

In our previous study on relations between conceptual and procedural knowledge when learning electromagnetism similar results were obtained [29].

6. CONCLUSION

The conducted assessment of undergraduate students' conceptual knowledge in researched physics domains with the applied CIs tests (the mod-WCI and the CSEM) has shown that electrical and computer engineering students have acquired a good knowledge of the basic concepts of electromagnetism, whereas they have had a rather low conceptual understanding of wave phenomena. Statistical analysis of the applied CIs has proved that the mod-WCI test has good discriminatory power but it is not a reliable diagnostic tool, either as a pretest or a posttest, for assessing conceptual knowledge of the tested engineering students. On the other hand, the CSEM test is a reliable test with adequate discriminatory power and it can be administered as a diagnostic tool for evaluation of engineering students' understanding of basic physical concepts of electromagnetism.

The majority of tested students have demonstrated insufficient understanding of basic concepts such as oscillation and waves taught in secondary schools and in university physics courses. It seems that some of students were guessing randomly when taking the mod-WCI test especially as a pretest. Although this testing method is very motivating for most of the students because it enables them to evaluate their progress and compare it to other students, it seems that some students lack inner (and outer) motivation for such testing.

Considerable difficulties of undergraduate engineering students in conceptual understanding of wave phenomena, which were noted both prior and after instruction in the calculus-based physics course, have been confirmed by low values of normalized gain. FEE-UNIOS undergraduate students' low gain confirms that traditional instruction methods and strategies have dominated over interactive ones. The obtained results indicate the need to develop and introduce new instructional methods in order to improve conceptual understanding of students during introductory engineering courses. Certain students' misconceptions in this domain have been identified and they related to conceptual understanding of wave phenomena which include characteristic values describing wave motion and their dependence, mathematical description of wave and wave equation, but also specific cases of wave phenomena such as superposition of waves and standing waves. It could be expected that through further instruction the misconceptions detected by this test will be explained and replaced by concepts.

A rather low correlation between engineering students' conceptual and procedural performance in research physics domains suggests that in these physics domains conceptual and procedural knowledge are developed independently of each other. Conceptual knowledge seems to develop much more gradually, and students do not necessarily obtain valid conceptual understanding after introductory engineering or physics courses. Problem-solving exercises can improve students' performance in the exam improving in that way students' procedural knowledge. However, developing students' procedural skills by using problem exercises during calculus-based physics courses, does not significantly enhance students' conceptual knowledge. Besides, students' procedural skills are often limited by their (in)competence in mathematics which is one of the best single predictor of engineering success. Therefore, there is a need to broaden the view of what type of knowledge is valued and assessed in engineering education.

The presented study of engineering students' knowledge by using applied CIs tests should contribute to a deeper understanding of engineering students' learning behavior and outcomes.

The CIs have also been recognized as a valuable diagnostic instrument for assessment of students' conceptual knowledge in various domains of STEM disciplines. The multiple-choice CIs used in physics education research, have been adapted to engineering education as well. Nowadays, the CIs have been designed for a few specific engineering disciplines such as signals and systems, electric circuits, computer engineering, electromagnetics, strength of materials, thermodynamics and fluid mechanics.

Although the development and application of suitable CIs is quite demanding, it is advisable to use such tests for instruction and assessment in engineering education.

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