Journal of Engineering Education Transformations ,
Volume 37 , No. 1 , July 2023 , ISSN 2349-2473, eISSN 2394-1707

10.16920/jeet/2023/v37i1/23130

Using Concept Inventory for Assessing Conceptual Knowledge in the Signals and Systems Course

Rashpinder Kaur[1], Archana Mantri[2], Prathiba Nagabhushan[3], Gurjinder Singh[4]
[1, 2, 4] Department of Electronics and Communication Engineering,
Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India
[3] Department of Psychology, St. Mary MacKillop College, ACT, Australia
[1]rashpinder.kaur@chitkara.edu.in
[2]archana.mantri@chitkara.edu.in
[3]prathiba.nagabhushan@mackillop.act.edu.aus
[4]gurjinder.singh@chitkara.edu.in

Abstract: The engineering schools usually target problem-solving skills in students instead of conceptual development, which is an essential skill for transformation from novice to professional engineer as per the program objective. Improving a student's conceptual knowledge can help students understand a problem better and develop a better solution. Conceptual understanding also assists students in identifying gaps in their problem-solving techniques. This paper attempts to administer a Signal and System Concept Inventory (SSCI) to test the conceptual knowledge of core concepts of signals and systems course and then identify the correlation of post-test scores with the student's performance in the end-term exam. The result shows that the students who scored above 80% in concept inventory also performed outstanding in the end-term examination. The result also indicates that most of the students able solve questions on background mathematics and pole-zero plots but struggled with convolution and Fourier analysis.

Keywords: concept inventory, conceptual understanding, assessment, engineering education

Gurjinder Singh
Department of Electronics and Communication Engineering,
Chitkara University Institute of Engineering and Technology,
Chitkara University, Punjab, India
gurjinder.singh@chitkara.edu.in

1. Introduction

"Engineering is a profoundly creative process" (Taraban, Anderson, et al., 2007) is rightful claim to define the nature of professional engineering because it reflects a sense of the mindset and skill levels required for engineering students according to ABET engineering standards. Assessment methods are critical in evaluating student learning and skills, so it is crucial to choose the style of assessment that will help the student become a reflective thinker and successful problem solver. Also, preparing the students to become dextrous in solving problems in their domain is critical.

The engineering education community emphasizes that researchers learn about the initial stages of knowledge and development of skills in engineering students, which can help develop teaching methodologies, learning aids and initiation towards curriculum reform (Taraban, Anderson, et al., 2007). It also encourages researchers to gain theoretical and pedagogical knowledge about misconceptions held by the students, to gain an understanding of how students acquire skills for scientific comprehension and develop the problem-solving skills to become skilled engineers.

The initial stages of learning in an engineering area consist of declarative and procedural knowledge (Taraban, et al., 2007). The student's ability can be classified into declarative knowledge (definitions, facts, and concepts) and procedural knowledge (how the students use this knowledge and approach to solve problems). According to cognitive theories of skilled problem-solving, acquiring and using declarative knowledge is essential for effective performance. Concept learning, making inferences, and categorization are distinct components of engineering skills closely associated with practical problem-solving. However, problem-solving is procedural mainly because it is based on action-oriented knowledge and extracts a particular form of memory that stores procedural knowledge. Research reported that most students spend most of their study time developing problem-solving skills and very little time reading textbooks, which results in more procedural knowledge and less conceptual knowledge in students. Thus, even engineering students with outstanding academic backgrounds often need a deeper understanding of the concepts and principles that underline their training areas (Streveler et al., 2008).The above literature reveals the significance of procedural and conceptual knowledge as an essential skill required for any engineering student to become a professional engineer. The standard examination system meets the need only for assessing procedural knowledge. But it is also essential to assess conceptual understanding so that students can learn content and apply knowledge in different contexts. Conceptual knowledge can be measured if the teacher knows the student is learning. There is one parameter known as learning gain to measure whether a student is learning. Learning gain is defined by HEFCE (Sands et al., 2018) as an attempt to measure the improvement in professional and personal development attributes made by students during their study period of higher education. These attributes can be measured at discrete times when students' progress from the first year to graduation with a durable assessment to retain their learning up to and beyond graduation. So, to assess technical knowledge, the evaluation must be based on gauging problem-solving skills as well as conceptual understanding depending upon various qualitative and quantitative measurements (Boles et al., 2015).

The reliability of assessment tools to evaluate student thinking and reasoning is a significant challenge in assessing engineering students' conceptual understanding. It is easy to evaluate procedural knowledge as compared to conceptual knowledge. For instance, the teacher could design a question to test the students to evaluate whether they could correctly apply the process of calculation for Fourier transform sinusoidal signal. However, this rote assessment would not answer if the students were fully aware of the concept of the Fourier transform or its proper application for sinusoidal signals. Conventional methods of assessments/standard exams are inadequate to assess these complex outcomes of engineering education (Taraban, DeFinis, et al., 2007). Innovative assessments are required to meet these goals, which can give us deep insight into how a student approach and thinks about concepts and problems of the engineering domain.

Concept Inventory (CI) (Streveler et al., 2008) is one of the instruments which meet all the required skills discussed above and is specially designed to analyze the student's conceptual understanding. The CI is an effective tool to measure learning gain (Boles et al., 2015) because it is developed to measure student thinking rather than declarative and procedural knowledge of signal analysis fundamentals. It consists of multiple-choice questions to probe students' thinking, and the choices for each question include students' misconceptions about their incorrect understanding of the fundamentals. The term 'misconception' shouldn't be interpreted as misunderstanding (Boles et al., 2015); it is an alternative view of what the students hold about knowledge according to their experiences in life. The utility of multiple-choice-based concept inventory is ideal for testing conceptual understanding without scores being conflated by vocabulary knowledge, reading comprehension, or mathematical knowledge in assessing large classes in less time and can provide instant feedback to the students. The concept inventories have been developed for engineering courses such as thermodynamics, electromagnetism, signals and systems, statistics, etc. It is widely used in various universities in countries other than India to measure the students' conceptual understanding. Although the internal assessments and traditional exams are there to assess student's procedural knowledge, the concept inventory is different from these assessment techniques due to the following reasons (Sands et al., 2018):

- The questions in the Inventory are designed so that the possible multiple-choice answers include common misconceptions of students and correct answers, which are the true interpretation of the concept and require little computations.

- Students have been informed in advance regarding the summative assessment so that they can prepare themselves for it, which might result in the learning seen in the evaluation being sufficient only for the assessment and not retained for a longer period.

- Also, summative assessments are often examining mathematical or declarative knowledge.

So, the formative assessment of students using concept inventory compared to summative assessments can also help improve pedagogies.

This paper describes testing the conceptual knowledge of students studying signals and systems course using the Signals and Systems Concept Inventory (SSCI). The signals and system course is chosen because it is difficult for the students to understand due to abstract concepts unrelated to daily life (Fayyaz, 2014). The SSCI was developed in 2001,and it consists of 25 multiple-choice questions for each version i.e. Continuous-Time SSCI (CT-SSCI) and discrete-time SSCI (Kathleen E. Wage et al., 2005). Administering SSCI in various universities in the United States resulted in fruitful outcomes like choosing the correct order of teaching topics in a course, viz. (teaching continuous-time before discrete-time) to teach signals and systems (K. E. Wage et al., 2002). The SSCI (Padgett et al., 2011) is a flexible tool for visualizing and quantifying student conceptual understanding in different situations. The essential outcomes of deep knowledge comprise long- term retention of information and application of the gained knowledge to novel situations because the knowledge is not based on rote procedural knowledge (Kathleen E. Wage et al., 2006).

The use of concept inventory in India has yet to be widely reported. In western countries, however, it has been reported that the application of concept inventory is successful in improving the conceptual understanding of a large number of students, and it is already discussed earlier that to upgrade the professional skills of engineering students, there is a need of assessment tools like concept inventory in the education system (Rahmawati et al., 2018). The research questions addressed in this research work are:

- Does the level of students' conceptual understanding improve with the use of concept inventory?

- Do students who scored above 80% in concept inventory questions also perform well in the end term exam?

This paper describes the results of testing the CT-SSCI. Section 2 gives a brief overview of development and conceptual coverage of the CT-SSCI exam. Section 3 describes the methodology followed for research. Section 4 presents the results and discussions of SSCI testing, confidence level of students for each question attempted in SSCI and comparison with end term exam results. Section 5 provides summary of the paper.

2. Development of SSCI

The researcher wanted to use standard SSCI (Kathleen E. Wage et al., 2005) but could not get access to it, so the questions were designed using the concept table of continuous- time (CT) version of SSCI and were modified according to signals and systems course of Electronics and Electrical Engineering programme under Chitkara University, Punjab, India. A few questions (Q7, Q8, Q9, and Q19) of competitive exams, such asGraduate Aptitude Test Engineering (GATE) were added to make it compatible with Indian engineering education standards. The core concepts for SSCI are background mathematics, Linear Time-Invariant (LTI), convolution, pole-zero plots and Fourier analysis. The questions on filtering, windowing and bode plot in the original SSCI were excluded in the designed SSCI because these topics are part of the digital signal processing and control system curriculum and not of the signals and systems course. The SSCI consists of 20 multiple-choice questions and only includes questions from continuous time analysis of signals.

The concept table for SSCI developed for this research work is shown in Table 1. The concept of Q1 to Q3, Q4, Q6, Q7, Q11, and Q18 is the same as the original SSCI (Kathleen E. Wage et al., 2005), the rest of the questions have been slightly modified as compared to the original concept table of SSCI. The concept inventory consists of seven questions on

Table 1: Concept Table of CT-SSCI

Q. No	Topic Name	Category	Concepts
1	Background mathematics	Time reversal	Recognize the correct plot of p(-t) for given plot of p(t).
2		Time shift	Recognize the correct plot of p(t-1) for given plot of p(t).
3		Basic signals	Recognize the plot of u(t)-u(t-2)

4	LTI	Time Invariance	For the given plots of input and output, recognize the plot of output, if input is shifted with time
5	Convolution	Convolution	For given plot of x(t), choose the plot of output signal for convolution of x(t) with itself
6		Convolution and LTI	For given plot of input signal x(t) and output h(t), choose the output of LTI
7	LTI	LTI properties	For the given system, input x(t) and output y(t), match the correct property of LTI for different relations between input and output
8			For the given system, inputis given as equation and impulse response h(t) is given as graph, choose the correct properties possessed by the system
9	Pole zero plots		Recognize the correct impulse response of causal system
10	Fourier Analysis	Fourier series	Identify the components ofgiven waveform of trigonometric Fourier series
11	Fourier Analysis	Fourier series	Select the best representation of equationfor the given waveform ofperiodic signal x(t)
12	Background mathematics	Differential equation	Recognize the form of solution to LCCDE
13	Fourier Analysis	Fourier series	Match the signals which consists of Fourier representation of different signals
14	Pole zero plots	Causal	Given set of pole-zero plots, choose the plot for stable and causal system
15			Given set of pole-zero plots, choose the plot for stable and non-causalsystem
16		Type of impulse response	Choose the plot for decaying exponential impulse response
17	Fourier Analysis	Fourier transform	Find Fourier transform for DC signal
18			Find the plot of R(jw)
19			Find the frequency response H(w)
20			Select the plot of magnitude response

Fourier analysis, so it has maximum weightage in the concept inventory, whereas the number of questions based on the convolution concept is 2, so it has the least weightage.

The question no.6 of convolution from the signals and systems concept inventory is shown below.

Q6. The input signal x(t) and its impulse response h(t) is given as in Figure 1.

What will be the output of Linear time invariant (LTI) system y(t)?

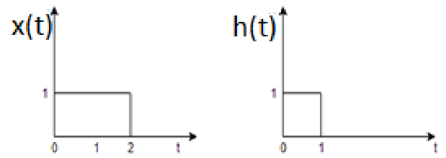


Fig. 1: Input Signal and Impulse Response

The choices given to the students to answer this question consists of one correct and three distracters are shown in Figure 2. The students need to compute the output of the LTI system when an impulse response h(t) is equal to a square pulse, and the input consists of a rectangular pulse. The correct answer for this problem is the convolution of the input with the impulse response, which results in a trapezoidal pulse option (d). The distracters for this question were designed to probe whether students multiply both signals and perform addition instead of convolving.

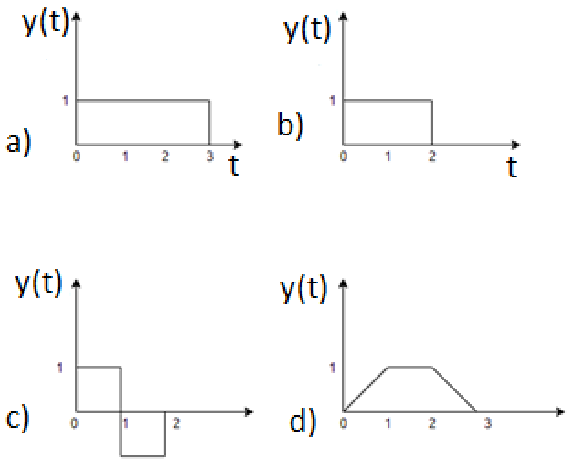


Fig. 2: Output of LTI system from (a) to (d)

3. Research Methodology

This section briefs about the participants, materials and procedure applied for this research work.

A. Participants

The test group consisted of 43 undergraduate Electronics and Communication Engineering students studying signals and systems course at Chitkara University, Punjab, India. Of the 43 respondents, the number of male students was 29, and the number of female students was 14.

B. Materials

The teacher teaching this course acted as a researcher for all the research work carried out and presented in this paper. The teaching pedagogy adopted for teaching and improving the students' understanding is based on active learning and interactive platforms like canvas. Printed copies of the question papers of SSCI were provided to the students along with the blank sheet so that student could write their justification(s) for choosing the options for each question.

C. Procedure

The concept inventory was administered in the last teaching week of semester. All the students studying this course appeared for the test. The students were allotted one hour for completing the test. At the end of each question in the inventory, the student had to select their confidence level (on a 4-point Likert scale) shown below:

1: Random guess; 2: Low confidence; 3: Average confidence; 4: Highly confident

Data from test were collected and analyzed to verify the intention behind development of SSCI.

4. Results and Discussions

The student's performance in the concept inventory was gauged and analyzed in essential topics of signals and systems. The SSCI test scores were reported on a scale of 0-100, with 4 points for every correct answer for each question on the CT-SSCI (Kathleen E. Wage et al., 2011). This section is divided into three subsections: results, discussions and findings of the study.

A. Results

There were five topics based on the core concepts of signals and systems. The average performance of all students in each topic (red bar) with respect to the total weightage of each topic (blue bar) was plotted in the graph in Figure 3. The student performance is categorized into three levels: excellent, average, and poor. If the student performed above 80% in the post-test, then his performance was excellent; student performance below 40% was categorized as poor, and the performance range between 50 to 80% was categorized as an average performer. This analysis revealed that the performance in background mathematics was excellent at 80%, moderate at 60% in pole-zero plots and low at 30% in convolution.

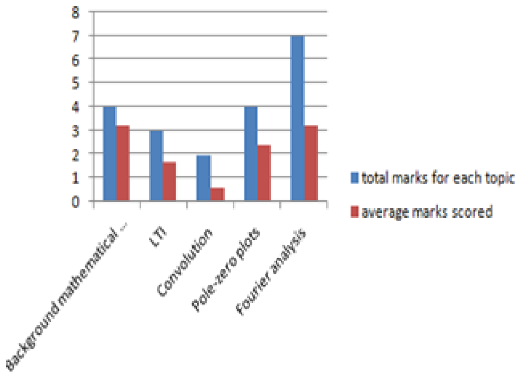


Fig. 3: Classification of student performance in the inventory for each topic

The performance of students in the convolution topic was poor. Only four students out of 43 had chosen the correct choice for both questions of convolution. Question 6 on convolution is already discussed in section 3. The Q5 consisted of a plot of the unit step signal as input x(t) and using the given expression of convolution, y(t)=x(t)*x(t)in the question, students had to recognize the plot of output y(t). Very few students answered this question correctly. Most students (40%) did not recognize the convolution symbol; they confused it with the multiplication operation and answered incorrectly. This result was consistent with testing the students' ability, indicating rote procedural knowledge, and might not be related to their conceptual understanding.

The student's confidence level for every question under different topics was analyzed using a line graph. The confidence level of the individual student for each question on the topic of background mathematics was illustrated with a line graph, as shown in Figure 4.

Most of the students showed high confidence for Q2 and Q3. The confidence level for Q12 fluctuated between all four levels, which implied that the students needed help to solve this question. The analysis of student's confidence level in the LTI topic was interpreted and shown in Figure 5.

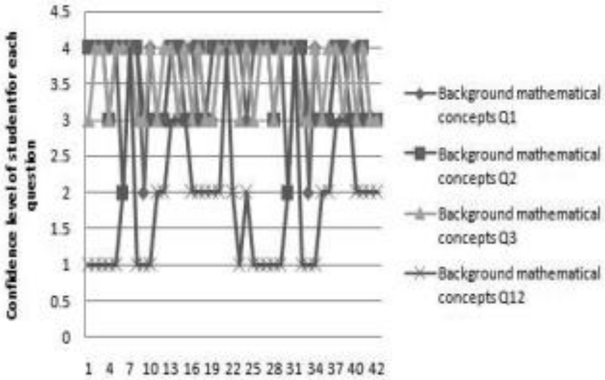


Fig. 4 : Confidence level of students on background mathematics

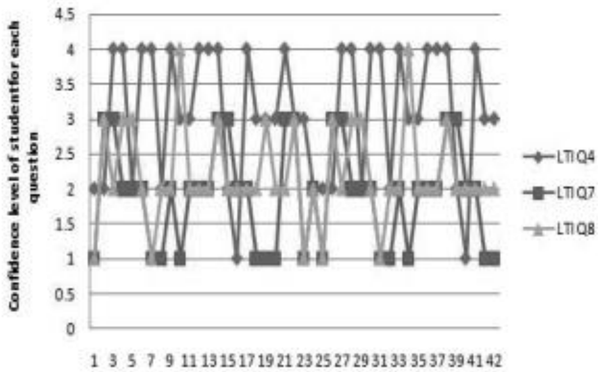


Fig. 5: Confidence level of students on LTI

The graph shows that most students have shown high confidence for Q4 and average confidence for Q8. They find Q7 difficult as only two students have stated high confidence, and most selected low confidence to solve this question. The confidence level of students in questions on the topic of convolution is very clear from the graph shown in Figure 6. Most of the students chose n high and average confidence to solve Q5, and the confidence level of students in solving Q6 was very low.

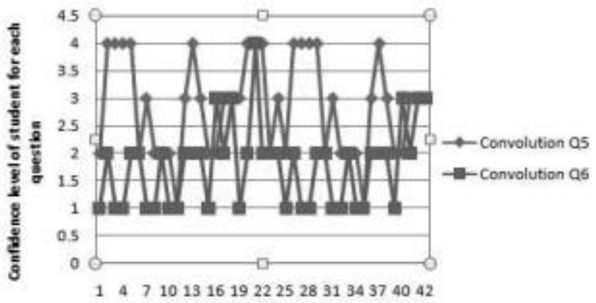


Fig. 6: Confidence level of students on convolution

As shown in Figure 3, students' performance in the convolution topic was poor. Many students attempted Q5 wrongly, and the graph displayed a selection of high confidence by the majority of the students because they thought it was an easy question and applied multiplication instead of the convolution operation.

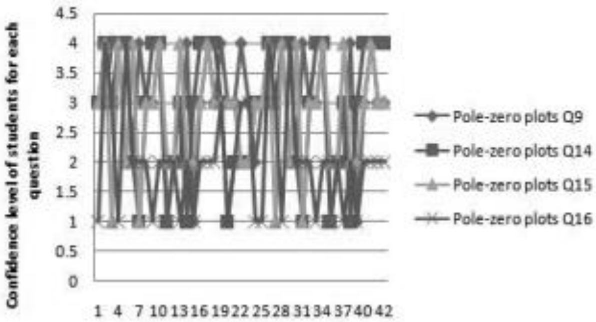


Fig. 7: Confidence level of students on pole zero plots

The confidence level of students in pole-zero diagrams questions shown in Figure 7 reveals that students were able to solve Q14 and Q15 compared to Q9, and more students chose low confidence for Q16.

There are a maximum number of questions of Fourier analysis in the concept inventory, so it is not easy to interpret due to overlapping results. The graph showed in figure 8 displays that the confidence of most of the students in Q11 and Q19 is high. The students found Q18 and Q20 confusing as their confidence levels fluctuate between four levels. Some selected random guesses, and some chose between low and average confidence levels. A similar scenario is for therest of the three questions of Fourier analysis.

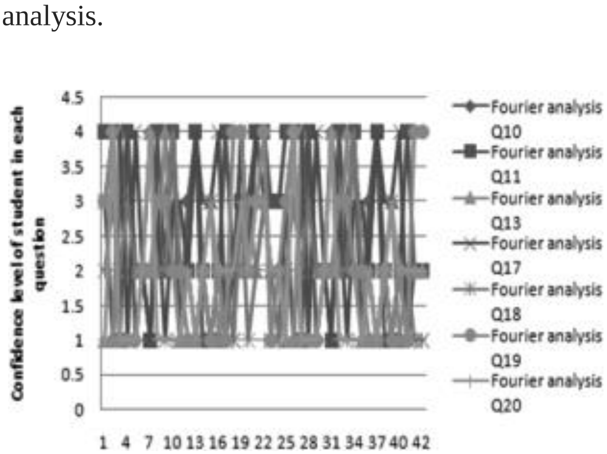


Fig. 8: Confidence level of students in Fourier analysis

The literal inference of performance and confidence level of students for questions of each topic displayed in Figures 5, 6, 7, and 8 has depicted in Table 2 below:

Table 2: Summary of student's performances and their confidence level

Q	Performance	Students' Confidence	Explanation
1	Average	Vary between low to high	Most of the students were able to solve the questions
2	Excellent	High	
3			
4			Majority of the students able to apply the time shifting concept.
5	Poor	Vary between low to high	Revealed student's misconception about convolution
6	Poor	Low	Students failed to get the correct answer due to inability to apply graphical method
7	Average	Average	Students were unable to apply LTI properties
8			
9	Average	Average	Students recognized the causal system
10	Average	Average	It was basic question related to Fourier series
11	Average	High	Student answered it correctly
12	Low	Low	Student find it difficult to solve
13	Poor	Low	Some students were not clear about the wording of the question
14	Excellent	High	Students had good understanding about causal/non-causal system
15	Excellent		
16	Below Average	Low	Failed to recognize the impulse response of exponential signal
17	Average	Average	Most of them answered correctly
18	Poor	Low	Students find this question difficult
19	Poor	Low	Students unable to apply the Fourier concept in frequency response of signals
20			

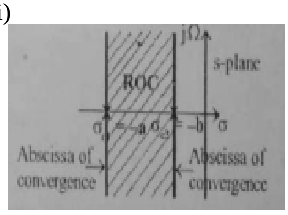
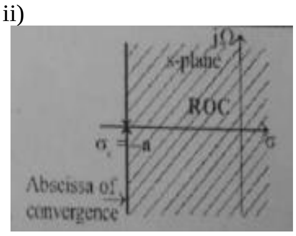
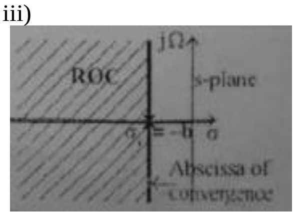
B. Discussions

The data analysis in a tabulated form indicates that if a student performed well on different topics in the concept inventory, his confidence level was also between average and high. Another observation is that poor performance correlated with low confidence and more chances of guessing. The improved student performance in pole-zero plots and background mathematics revealed that they could answer the questions correctly, so they have a better understanding of the concepts (answer to research question 1). But there is one major drawback in the multiple-choice format of concept inventory: if a student selects the correct answer, and his choice of selection was based on guessing, then it highlights the case where the multiple-choice format of the concept inventory failed to reflect accurate conceptual understanding. In this case, a student receives marks for a correct answer, but the instructor needs to know the reason behind the right selection of choices made by the student. The second point captured while investigating the results is that it needs to provide a clue to the instructor about how the respondent arrived at the incorrect selection so that he can help the students in clearing their misconceptions. These drawbacks can be overcome with subjective tests/comprehensive tests and verbal protocol methods to know the student's thought process to reach the correct solution.

To answer the second research question, student's performance in concept inventory is compared with their end-term results. The question in the end-term exam on the pole-zero plot is asked, and it is shown in Table 3.

The students had to match each impulse response of causal, anti-causal, and non-causal signals to their correct pole-zero diagrams and depict its ROC. Similar questions were asked in the concept inventory Q14-16. The concept inventory results reported that 37% of the students had answered these questions correctly, and these students were able to correctly attempt similar questions at the end-term exam. Figure 9 presents the enhanced student performance

Table 3: Impulse Response and the Relevant Pole Zero Plots

<table>
<tr><th>h(t)</th><th>Location of poles and ROC</th></tr>
<tr><td>a) $h(t) = A^{-at}\ u(t)$</td><td>i)

</td></tr>
<tr><td>b) $h(t) = e^{-at}\ u(-t)$</td><td>ii)

</td></tr>
<tr><td>c) $h(t) = e^{-at}u(t) + e^{-bt}u(t)$</td><td>iii)

</td></tr>
</table>

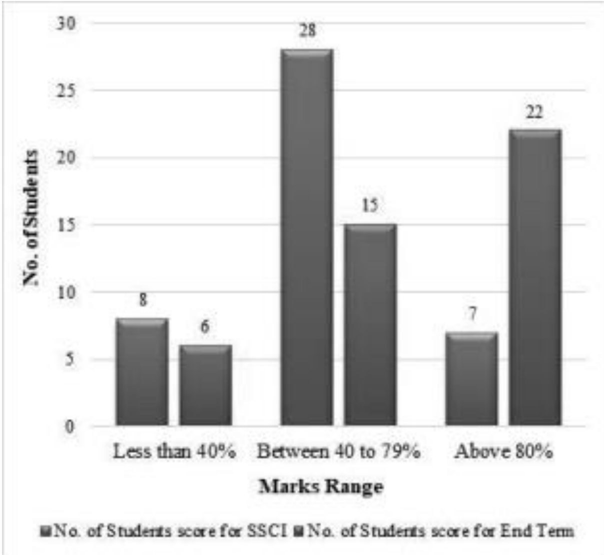


Fig. 9: Comparison Of Student's Performance In End Term And SSCI

in the end-term exam; this was visible through the increased number of students scoring above 80% in the end-term examination compared to SSCI. The blue bar in the range of marks score between 40 to 79% was higher as compared to the red bar, which meant that a greater number of students scored in concept inventory (SSCI) in that range.

The mean of students' performance in SSCI and end term is shown in Table 4. The mean score of SSCI was 56.16, with a standard deviation of 18.21, and the mean value of the end-term exam was 73.02, with a standard deviation of 20.53, as reported in Table 4. This statistical analysis showed improvement in conceptual understanding for some conceptual dimensions, such as pole-zero plots and background mathematical concepts included in the concept inventory. The large value of standard deviation (20.53) in the end-term exam suggested that the students with improved conceptual understanding using CI and performed well in the end-term exam.

The Pearson correlation analysis reported a statistically significant p-value of 0.005, indicating a positive correlation between the performances of students on the concept inventory questions to end term exam questions on the same topics.

Table 4: Statistics of SSCI and End Term Exam

Exam	N	Mean	S.D.	Std. error mean
SSCI	43	56.1628	18.21	2.77
End term	43	73.0233	20.53	3.13

C. Findings of the Study

Administration and analysis of CI helped in broadening the conceptual knowledge of students. Further, with more practice and effective teaching pedagogies, it would be helpful in the development of their problem-solving skills and their thinking, which can make them proficient and life- long learners.

Using CI in the curriculum, the researcher has also enhanced their own conceptual skills, learnt effective pedagogical methods to teach the course effectively and gained insights into students' misconceptions and their thinking about the concepts taught. This research work is beneficial for the teachers too. The research community can be motivated to design and popularize the use of concept inventories in engineering education to improve the quality of knowledge and skills of Engineering students.

5. Conclusion

This paper presents the analysis of the performance of students for various core concepts of signals and systems course using concept inventory in terms of conceptual understanding and confidence level. The analysis of administering concept inventory reveals the improved conceptual understanding of students using SSCI that helped them to perform well in the questions based on similar conceptual dimensions in the end-term exam. However, their conceptual understanding of the topic of convolution and Fourier analysis still existed due to their inability to apply the right concept to get the correct answer. One of the limitations of concept inventory found during this research is the inability to get an insight into the student's thinking and process for solving each question. The classroom discussions can be used to clear identified misconceptions and allow students to explain and explore these concepts. The other instructional tips are to use a reflective approach to discuss and think about concepts in the classroom. This study is a starting point of research that measures the conceptual knowledge of students with the use of concept inventory inconsistent with the achievement of one of the program objectives of engineering graduates to become lifelong learners and professionals. The next step in the research will include a written conceptual test along with the interviews using think-aloud process to get deep insight into the thought process of the students.

References

[1] Boles, W., Goncher, A., & Jayalath, D. (2015). Uncovering misconceptions through text analysis. 6th Research in Engineering Education Symposium: Translating Research into Practice, REES 2015, July, 13–15.

[2] Fayyaz, F. (2014). A qualitative study of problematic reasoning's of undergraduate electrical engineering students in Continuous Time Signals and Systems courses. http://docs.lib.purdue.edu/open_access_dissertations.

[3] Padgett, W. T., Yoder, M. A., & Forbes, S. A. (2011). Extending the usefulness of the Signals and Systems Concept Inventory (SSCI). 2011 Digital Signal Processing and Signal Processing Education Meeting, DSP/ SPE 2011 Proceedings, 204-209. https://doi.org/10.1109/DSP-SPE.2011.5739212

[4] Rahmawati, Rustaman, N. Y., Hamidah, I., & Rusdiana, D. (2018). The development and validation of conceptual knowledge test to evaluate conceptual knowledge of physics prospective teachers on electricity and magnetism topic. Jurnal Pendidikan IPA Indonesia, 7(4), 483-490. https://doi.org/10.15294/jpii.v7i4.13490

[5] Sands, D., Parker, M., Hedgeland, H., Jordan, S., & Galloway, R. (2018). Using concept inventories to measure understanding. Higher Education Pedagogies, 3(1), 173–182. https://doi.org/10.1080/23752696.2018.1433546

[6] Streveler, R. A., Litzinger, T. A., Miller, R. L., & Steif, P. S. (2008). Learning conceptual knowledge in the engineering sciences: Overview and future research directions. Journal of Engineering Education, 97(3), 279–294. https://doi.org/10.1002/j.2168-9830.2008.tb00979.x

[7] Taraban, R., Anderson, E. E., DeFinis, A., Brown, A. G., Weigold, A., & Sharma, M. P. (2007). First steps in understanding engineering students growth of conceptual and procedural knowledge in an interactive learning context.

Journal of Engineering Education, 96(1), 57–68. https://doi.org/10.1002/j.2168-9830.2007.tb00915.x

[8] Taraban, R., DeFinis, A., Brown, A. G., Anderson, E. E., & Sharma, M. P. (2007). A paradigm for assessing conceptual and procedural knowledge in engineering students. Journal of Engineering Education, 96(4), 335–345. https://doi.org/10.1002/j.2168-9830.2007.tb00943.x

[9] Wage, K. E., Buck, J. R., Welch, T. B., & Wright, C. H. G. (2002). Testing and validation of the signals and systems concept inventory. Proceedings of 2002 IEEE 10th Digital Signal Processing Workshop, DSP 2002 and 2nd Signal Processing Education Workshop, SPE 2002, 151-156. https://doi.org/10.1109/DSPWS.2002.1231094

[10] Wage, Kathleen E., Buck, J. R., & Hjalmarson, M. A. (2006). Analyzing misconceptions using the signals and systems concept inventory and student interviews. 2006 IEEE 12th Digital Signal Processing Workshop and 4th IEEE Signal Processing Education Workshop, 123–128. https://doi.org/10.1109/DSPWS.2006.265451

[11] Wage, Kathleen E., Buck, J. R., Hjalmarson, M. A., & Nelson, J. K. (2011). Signals and systems assessment: Comparison of responses to multiple choice conceptual questions and open-ended final exam problems. 2011 Digital Signal Processing and Signal Processing Education Meeting, DSP/SPE 2011 - Proceedings, 198–203. https://doi.org/10.1109/DSP-SPE.2011.5739211

[12] Wage, Kathleen E., Buck, J. R., Wright, C. C. H. G., & Welch, T. B. (2005). The signals and systems concept inventory. IEEE Transactions on Education, 48(3), 448–461. https://doi.org/10.1109/TE.2005.849746