Enhancement of Educational Methods to Improve Understanding of Convolutional Operations through Impulse Response Measurement

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The National Institute of Technology (KOSEN), Gifu College consists of five departments: Mechanical Engineering, Electrical and Computer Engineering, Electrical Control Engineering, Civil Engineering, and Architecture. Fourth-year students in the Department of Electrical and Computer Engineering conduct a signal processing experiment as part of the "Electrical and Computer Engineering Laboratories" course. The purpose of this experiment is to facilitate students' understanding of signal processing by linking mathematical operations with tangible outcomes. However, many students tend to focus solely on the results of the processing without fully grasping the underlying principles. Furthermore, lectures in related fields often emphasize mathematical concepts, offering few opportunities for students to connect theory with real-world physical phenomena.

To address these challenges, this study aimed to improve the educational approach used in the signal processing experiment. To enhance students' comprehension, a demonstration of room acoustic impulse response measurement was incorporated into the course. This initiative was a collaborative effort between faculty members and technical staff from both the Department of Electrical and Computer Engineering and the Department of Architecture. The class followed this sequence: preparatory study (acquisition of foundational knowledge), demonstration of room acoustic impulse response measurement (understanding practical applications), programming exercises (reinforcing mathematical operations), and report writing. The integration of hands-on demonstrations with theoretical instruction was intended to bridge the gap between abstract concepts and real-world applications.

This paper reports on the structure and educational effectiveness of the classes conducted in 2022 and subsequent years. An analysis of students' experimental reports indicated that the quality of submissions improved when the demonstration was included. Additionally, a student questionnaire revealed that the demonstration had a positive impact on students' understanding of and interest in the subject.

Keywords: *experiment, teaching method, mathematical processes and physical phenomena, academic interest of students*

Introduction

With the advancement of digital technologies in sound and acoustics, there is an increasing demand for engineers with specialized knowledge and skills in these areas. In response to this need, we have been conducting a signal processing experiment as part of the course "Electrical and Computer Engineering Laboratories" since 2021. In 2022, we introduced a demonstration involving room acoustic impulse response measurements to enhance the educational experience. This course is offered to fourth-year students (approximately 19 years old) at the National Institute of Technology (KOSEN), Gifu College.

This paper presents an overview and evaluation of the experiment in the following structure: First, the course outline and educational objectives are described. Next, we detail the enhancements made to the teaching methods. We then present the results and discussion for academic years 2022 and 2023. Finally, we report ongoing developments in 2024 and 2025.

Overview of the Course

The "Electrical and Computer Engineering Laboratories" course for fourth-year students is designed to deepen their understanding of both fundamental and applied technologies in electrical, electronic, and computer engineering through hands-on experimental practice. Students are required to submit a report for each experiment after completing the class. In this course, students are divided into ten groups of 4–5 members to conduct practical experiments, with each student responsible for writing their own individual report.

The course covers several experimental themes, one of which is the subject of this study. It consists of one weekly session, totaling 180 minutes, divided into two consecutive 90-minute periods. Each experimental theme is typically completed within a single-week session, although some themes extend across three consecutive weekly sessions. The course emphasizes student-led experimental activities, with multiple faculty members and technical staff supporting the process by explaining key points, checking experimental results, and conducting oral examinations.

Students conduct experiments based on manuals prepared by instructors. They are expected to read these manuals in advance and develop an understanding of the experimental procedures and objectives before class. At the end of each session, students deepen their understanding through oral examinations conducted by instructors.

After class, students are assigned individual study tasks and required to submit a written report. Each report includes a summary of the principles and theoretical background, a description of the experimental procedures and results, and a discussion of the findings. Through this process, students develop essential skills in the fields of electrical and electronic engineering and computer technology, such as investigation, analysis, research, and problem solving.

Improved Educational Methods

An experimental theme for signal processing was implemented in this course in 2021. In that year, we conducted a Multimedia Signal Processing experiment focused on programming exercises. In this experiment, students used Python to apply filters, perform convolution, and conduct frequency analysis on image and sound data. Since 2022, the experiment has specialized in signal processing in room acoustics, under the title “Acoustic Signal Processing.” In addition to conventional programming exercises, it includes a demonstration of acoustic impulse response measurements conducted in a room. The purpose of incorporating this demonstration was to provide students with an example of how acoustic signals are acquired in practice, thereby helping them understand the real-world application of signal processing.

As Tachibana (2012) notes, an impulse response is the output of a system when an impulse is applied as an input. It can be transformed using the Fourier transform to reveal the transfer characteristics of the system across a range of frequencies. In the context of architectural spaces, the room acts as a system. Therefore, the impulse response measured in a room characterizes the acoustic transmission path between the sound source and listening position at the time of measurement, effectively reflecting the acoustic properties of the room. During impulse response measurement, a test sound, such as an impulse, is emitted from a nondirectional speaker placed in the room, and both the direct and reflected sounds are captured by a microphone (Figure 1).

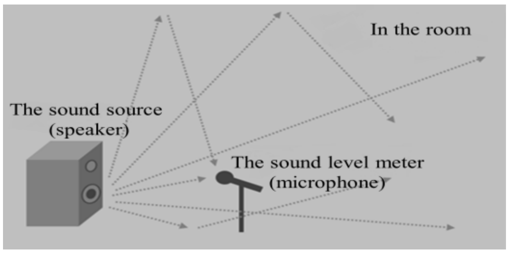


Figure 1. Overview of impulse response measurements

An impulse response demonstration was conducted using the TSP (Time-Stretched Pulse) method. This method was selected because it provides a high signal-to-noise ratio and enables accurate waveform acquisition, even in large spaces.

The TSP signal was generated by the acoustic analysis system DSSF3 real-time analyzer (Yoshimasa Denko), amplified by a YAMAHA XM4180 amplifier, and emitted through a coaxial nondirectional speaker (Listude, Scenery). Direct and reflected sounds were captured using a sound level meter (Ono Sokki, LA-1441). In accordance with International Organization for Standardization (ISO) guidelines ISO3382-1 (2009) and ISO3382-2 (2008), the sound source (speaker) was placed at the center of the room, and the receiving point (sound level meter) was positioned 1.0 meter away from the source. Both the speaker and sound level meter were set at a height of 1.5 meters from the floor, corresponding approximately to the height of a standing human ear.

Before the measurements, students were provided with a verbal explanation of the procedure. They then observed a live demonstration of the measurement, viewed the resulting impulse response waveforms, and listened to the corresponding audio outputs. After the demonstration, the same equipment was used to play and record several anechoic sound sources prepared by each student through the speakers.

The demonstration was conducted in the second gymnasium of NIT, Gifu College. This location was chosen because the large space and limited sound-absorbing surfaces made it easier for students to perceive acoustic reverberations.

In the proposed experimental method, students conducted programming exercises using impulse response data obtained from the measurements. This exercise aimed to help students understand signal processing by linking mathematical operations with tangible results. Specifically, the students performed convolution and frequency analyses using the Fourier transform.

Convolution is a mathematical operation widely used in image and sound processing. It involves two continuous functions, $f(t)$ and $g(t)$, and is defined by the following equation:

$$\int_a^b f(x)g(t-x)dx \tag{1}$$

In this experiment, the impulse response waveform is denoted as $h(t)$, and the convolution of the impulse response with an arbitrary input waveform $f(t)$ is calculated as follows:

$$h(t) * f(t) = \int_{-\infty}^{\infty} h(x)f(t-x)dx \tag{2}$$

The resulting waveform represents the original signal $f(t)$ with spatial reverberations of the room acoustics added through convolution with the impulse response.

The Fourier transform is another fundamental technique used in acoustic signal analysis. It decomposes a time-domain signal into its constituent frequency components, enabling visualization of their magnitudes in the form of a spectrogram.

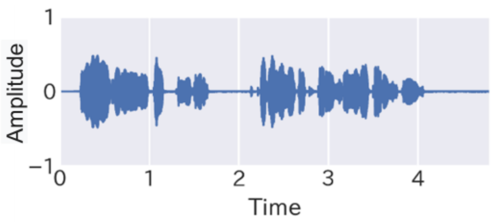
In this programming exercise, students wrote code in Python in the Information Processing Exercise Room at NIT, Gifu College. They used Google Colaboratory (Colab) as the Python environment, either on desktop computers in the lab or on personal laptops. Colab (2019) was selected for this exercise because it runs in a web browser and allows students to write and execute Python programs without setting up a local development environment. Its ease of use and accessibility make it an effective exercise platform.

For this programming task, students were provided with partially completed programs for performing convolution processing and frequency analysis using the Fourier transform. They were required to complete these programs by independently thinking through and writing the missing parts.

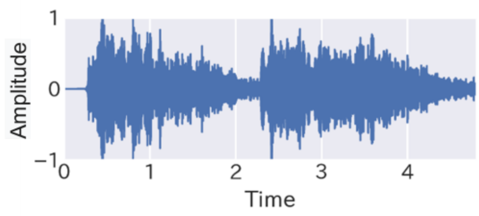
For convolution, students convolved the measured impulse responses with anechoic sound sources prepared in advance. The resulting sound sources, referred to as convolved sources, were anechoic sounds with artificially added reverberations. Students compared sound sources with added reverberations to those with anechoic sources played in the room by visualizing the waveforms and listening to audio playback. Comparisons were made visually by inspecting the waveforms and aurally by listening to the processed sounds.

In the frequency analysis task, students visualized the time variation of the frequency components of impulse responses using spectrograms. They confirmed that sound attenuation varies depending on frequency. Spectrograms were also generated for anechoic sources, convolved sources, and recordings made in a room using anechoic sources. These were compared in terms of frequency content to deepen students' understanding of how room acoustics affect sound.

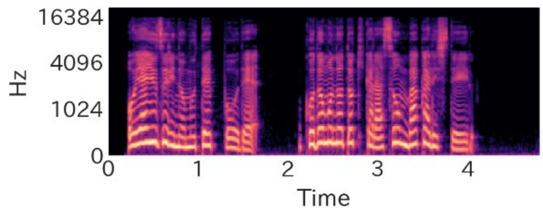
Students implemented Equation (1) in their programs and verified the results using the measured data. The spectrograms of the anechoic and convolved sources are shown in Figures 2, and the corresponding frequency response graphs are presented in Figures 3, respectively.



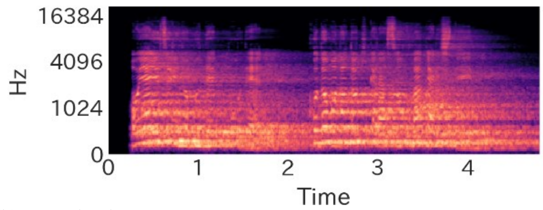
(a) anechoic source



(b) convolved source
Figure 2. Spectrogram of sources



(a) anechoic source



(b) convolved source
Figure 3. Frequency response of sources

The 2022 experiment was conducted as a group-based experimental theme, with students participating in sessions held on June 23, June 30, July 7, July 14, and July 21. Each day, six to eight students (two groups) participated, for a total of 37 students.

On the first day of class (June 23), a measurement demonstration was conducted under the guidance of a faculty member from the Department of Architecture. For subsequent sessions, technical staff from the Department of Electrical and Computer Engineering led the demonstrations.

The second gymnasium and the art room were used as venues for the measurement demonstration in 2022. As mentioned previously, the second gymnasium was selected because of its large space and minimal sound absorption. However, because temperatures in Gifu Prefecture exceeded 30°C from mid-June onward, it was determined that conducting the demonstration in the non-air-conditioned gymnasium posed a risk of heatstroke. Therefore, starting June 30, demonstrations were held in an air-conditioned art room with sufficient space. The experiment conducted in the art room is illustrated in Figure 4.

In 2023, the theme schedule for the "Electrical and Computer Engineering Laboratories" course was revised, and this experiment was conducted as a joint session for all students on May 26. As a result, 41 students participated in the demonstration of the actual measurement, which was held in the second gymnasium. The experiment conducted in the second gymnasium is illustrated in Figure 5.


Figure 4. Demonstration of actual measurement of impulse response in the art room

Figure 5. Demonstration of actual measurement of impulse response in the second gymnasium

Following the demonstration, a lecture on room acoustics was delivered by a faculty member from the Department of Architecture. The lecture covered topics such as an overview of impulse response waveforms, acoustic indices derived from impulse responses, the relationship between resonance and room geometry and volume, and an introduction to the signal-to-noise ratio. Because the experiment was conducted on a single day, all students were able to participate in the measurement demonstration, receive oral explanations, and attend the lecture-style presentation. This enhanced the specialization and cohesion of the course content.

Overview of the Evaluation

To evaluate the educational effectiveness of the proposed experimental method, students' comprehension was assessed based on their report scores. The grading criteria used in this study are presented in Table 1. The evaluation items were divided into four categories: *Formatting, Principles of the Experiment, Procedure and Results of the Experiment, and Discussion*. *Formatting* refers to the overall structure and presentation of the report; *Principles of the Experiment* involve a summary of background knowledge investigated before or after the class; *Procedure and Results* pertain to the experimental process and the data obtained; and *Discussion* reflects the interpretation and analysis of the results.

The scoring criteria shown in Table 1 were applied uniformly across all experimental themes in the course. The same instructors assessed the reports using these criteria in both 2022 and 2023 to ensure consistency in evaluation. Moreover, the instructional approach for writing reports remained unchanged across both years.

In addition, a questionnaire was administered to students to collect self-assessments of their understanding at three stages: before the class, after the class, and after submitting their reports. The questionnaire also included an open-ended section in which students could freely express their opinions on the class and evaluation process.

The questionnaire focused on five topics related to the content and principles of the experiment, aiming to assess students' perceived level of understanding:

a) Digital signal processing
b) Impulse response
c) Convolution operations
d) Frequency analysis using the Fourier transform
e) Mathematical operations and outcomes in digital signal processing

For each topic, students rated their level of understanding on a five-point scale at the time of completing the questionnaire. The scale was based on the achievement levels defined in the Model Core Curriculum (2025) and interpreted as follows:

Table 1. The grading criteria for the reports

	Scores					
	4	3	2	1	0	-1
Formatting					Formatting is consistent	Formatting is inconsistent
Principles of the Experiment			Describe the results of the survey in an easy-to-understand manner	Describe with reference to textbooks and other sources	Rough copy principles written in the procedure manual	No written principles
Procedure and Results of the Experiment	Clearly present with appropriate use of figures and tables	Interpret in own way and summarize in an easy-to-understand manner	Summarize such that others can read and understand	Some points are not clear to others	The procedure and results are lacking and unclear	No description of procedure and results
Discussion	Sufficiently analyze and discuss the results and describe his/her opinion and the content of the investigation in a logical manner	Analyze and discuss the results and logically describe by revisiting theoretical equations or creating new graphs	Analyze the results of the experiment and logically describe his/her opinion	Analyze the results of the experiment and describe in his/her own words	Repeat description of experimental results	No written discussion

1 - Cannot understand basic concepts
2 - Can understand basic concepts
3 - Can understand the content described in the experiment manual
4 - Can explain to others / perform basic processing
5 - Can describe in academic papers / apply in further studies

Results (2022 and 2023)

In 2022, 37 students participated in the class, and in 2023, 41 students participated.

Figure 6 shows the distribution of report scores and the percentage of students for the experimental theme in each year. For reference, the figure also includes results from the 2021 "Multimedia Signal Processing" experiment, which was conducted online due to the COVID-19 pandemic and involved 42 students.

As shown in Figure 6, the number of students who produced higher-scoring reports increased in both 2022 and 2023 compared with 2021. The average report scores were 7.3 in 2021, 8.0 in 2022, and 8.6 in 2023. In 2021, approximately 40% of the students scored 7 points, suggesting a relatively low level of understanding of the experimental content. In contrast, in 2022, most students scored between 7 and 9 points, with 8 points being the most common. In 2023, approximately 40% of the students achieved a perfect score of 10. These results indicate that the average scores in 2023 were higher than in previous years, reflecting a deeper understanding of the experimental content. Students were able to effectively summarize this understanding in their reports. Additionally, the higher scores in 2023 may be attributed to the participation of faculty members from the Department of Architecture in the lecture sessions.

A questionnaire survey was conducted with all students in 2022 and 2023. In 2022, 37 responses were collected before the experiment, 37 after the experiment, and 35 after report submission. In 2023, 41 responses were collected before the experiment, 40 after the experiment, and 36 after report submission.

Figure 7 presents a radar chart illustrating the average response values for each question in the 2022 comprehension questionnaire. The mean values increased gradually from the pre-experiment to the post-report stage, indicating an improvement in students' understanding through both experimental practice and report writing. Notably, item b) *Impulse response* showed the greatest increase, from 1.9 before the experiment to 3.6 after. Similarly, item c) *Convolution operations* increased substantially from 2.0 to 3.5. These results suggest that the hands-on experiment effectively enhanced students' understanding of convolutional processing in room acoustics.

Figure 8 presents a radar chart of the 2023 comprehension questionnaire results, which also demonstrates increased understanding across all question items following the experiment and report writing. The findings in Figures 7 and 8 indicate that the highest level of comprehension was consistently achieved for item b) *Impulse response* in both years.

In the free-response section of the questionnaire, positive comments such as "It was fun" and "It was easy to understand" were noted in both 2022 and 2023. However, in both years, some students also mentioned difficulties in understanding frequency analysis using the Fourier transform.

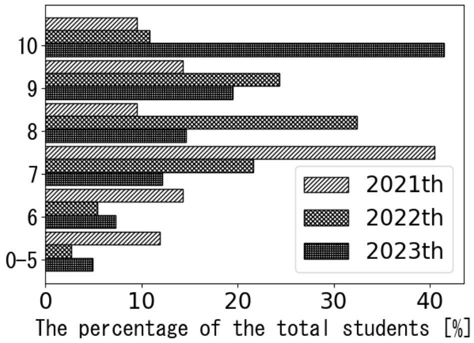


Figure 6. Results of grading of experimental reports

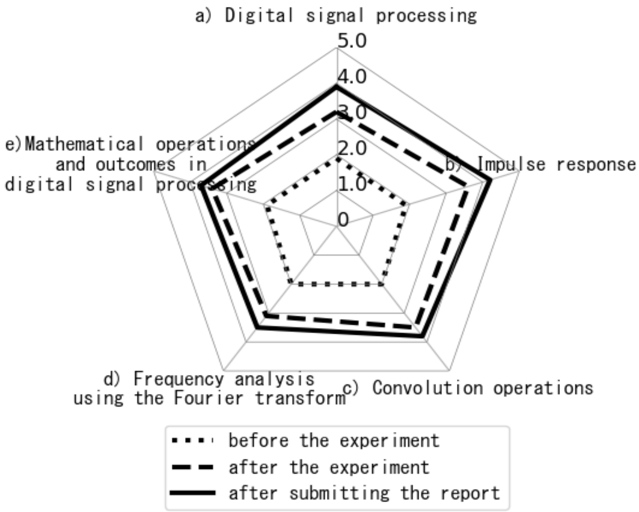


Figure 7. Results of student self-assessment in 2022

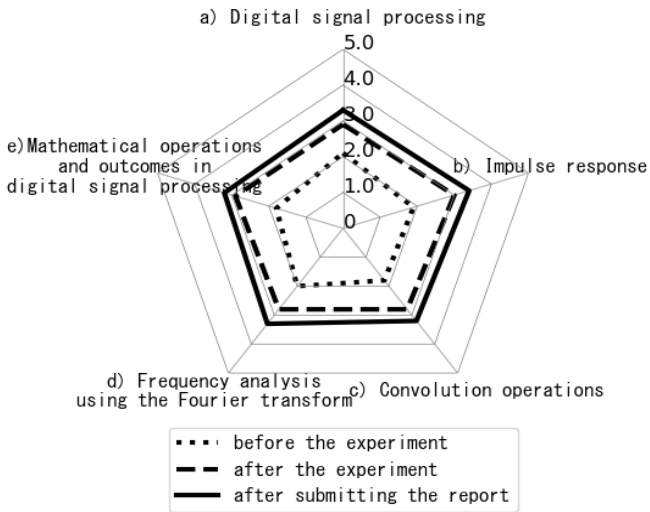


Figure 8. Results of student self-assessment in 2023

Discussion of the Results

The results of the experimental report evaluations indicated that incorporating a demonstration of actual impulse response measurements into the acoustic signal processing experiment significantly enhanced students' understanding of the subject matter. The questionnaire responses also revealed that students perceived an improvement in their comprehension as a result of the experimental practice. Moreover, the demonstration appeared to increase students' interest in specialized knowledge and techniques. In addition, during the lecture delivered by a faculty member from the Department of Architecture, students received a review of the demonstration along with an explanation of the characteristics of indoor acoustics. This lecture is considered to have helped students recognize acoustics as a more familiar and tangible phenomenon, thereby deepening their understanding of the underlying principles.

This positive effect is likely attributable to the use of a familiar topic, room acoustics, and the inclusion of real-world demonstrations, which helped students visualize the phenomena more concretely. Although signal processing is widely used in daily life, students rarely have opportunities to study it in an experiential context. In this experiment, students recorded the sound of an anechoic source they had prepared as it reverberated within the room and then simulated the same acoustics by applying reverberation through convolution in a programming exercise. This approach helped connect abstract mathematical concepts with tangible outcomes.

However, many students reported difficulty fully understanding frequency analysis using the Fourier transform. The experiment included programming exercises in which students generated and compared spectrograms from a frequency-domain perspective. They were expected to explore the underlying principles and practical applications of the technique independently. As a result, variations in individual understanding were observed.

Additionally, differences in students' performance evaluations and self-assessments between the academic years 2022 and 2023 were noted. These variations are believed to stem largely from differences in students' writing skills and levels of academic self-confidence.

The Development of the 2024 and 2025

In 2024, the experiment was conducted in the same format as in 2023, with no changes in the faculty members responsible for grading the reports or teaching report writing.

A total of 39 students participated in this theme in 2024. The average score for the reports on this experimental topic was 8.25, which is comparable to the average score in 2023. However, the score distribution in 2024 showed that 17 students received a score of 9 points. A closer examination of the content revealed that most students scored below 4 in the "Discussion" section. This suggests that they did not adequately fulfill the criteria outlined in Table 1, which state that students should "Sufficiently compare and analyze the results and describe his/her opinion and the content of the investigation in a logical manner."

Additionally, the self-assessment questionnaire indicated that the average score in 2024 was higher than in 2023, but lower than in 2022. The improved understanding of impulse response and increased comprehension following the experiments and report writing are consistent with trends observed in both 2022 and 2023. Furthermore, several positive comments were noted in the free-response section, and no negative comments were reported. This positive feedback is attributed to the effectiveness of the impulse response demonstrations and lectures delivered by the Faculty of Architecture, which were particularly meaningful to the students.

This experiment is scheduled to continue through 2025. Additional quantitative evaluation methods beyond reports and questionnaires are being considered.

Conclusions

This paper reports on the educational impact of introducing room acoustics measurement and analysis into the experimental theme "Acoustic Signal Processing" for fourth-year students in the Department of Electrical and Computer Engineering at NIT (KOSEN), Gifu College. The proposed approach effectively increased students' interest in acoustic signal processing and improved their understanding of impulse response and convolution operations.

Moving forward, programming exercises will be further refined to support a deeper understanding of frequency analysis using the Fourier transform. Additionally, the implementation of step-by-step quizzes will provide a more quantitative assessment of the learning outcomes associated with this educational method.

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