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Experience-Based Lecture for Vibration Engineering Using Dual-Scale Experiments: Free Vibration of an Actual Seismic Building and Controlling the Vibration of Scale-Down Experimental Model

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ABSTRACT This paper proposes an experience-based lecture style that offers dual-scale experiments in combination. Lectures for vibration engineering were designed based on the proposed style and offered to undergraduate students. In the proposed style, experiments on free vibration on a seismic building for second-year students and advanced vibration control using an effective device for fourth-year students are examined in combination. The lecture style trials were repeated twice, once each in 2015 and 2016, with about two hundred second-year students; the students felt the free vibration of the five-story building which had a 6,100 ton weight inside and witnessed the mechanism of the base-isolated layer. To follow the demonstration steps, we developed an experimental device. The experimental device is composed of a vibration component corresponding to a building, and a motor cart with a handle corresponding to the ground. These are connected via a linear actuator that can exert one-dimensional force on the vibration component as a function of the input voltage. In the lectures conducted in 2017 and 2018, the students oscillate the cart and observe the motion of the vibration component. In addition, the virtual reality cameras for offering students a visually rich experience attracted students' interest. The questionnaire results showed that almost all of the students valued the lectures as useful. Since most of the students answered that the combination of the large-scale demonstration and scale-down experiment was useful, the proposed lecture style achieved the expected overall goals.

INDEX TERMS Engineering education, students experiments, vibration control, V-shape education style.

I. INTRODUCTION

In engineering education, teaching methods that motivate the students are quite important. To satisfy the requirement to be an expert in the field, students need strong theoretical foundations as well as practical skills. It has been revealed that traditional teaching styles that mainly rely on passive and non-interactive approaches, such as lectures, homework assignments, and tests, produce less effective educational results [1]. An individual student's in-class learning depends on his or her interests in the topic and innate abilities [2]. Since students tend to forget what is simply said or shown, pictures, videos, or even small experiments are introduced in a class to motivate students. Various approaches have been proposed for a smooth transition from lecture-based knowledge received in classrooms to practical skills used

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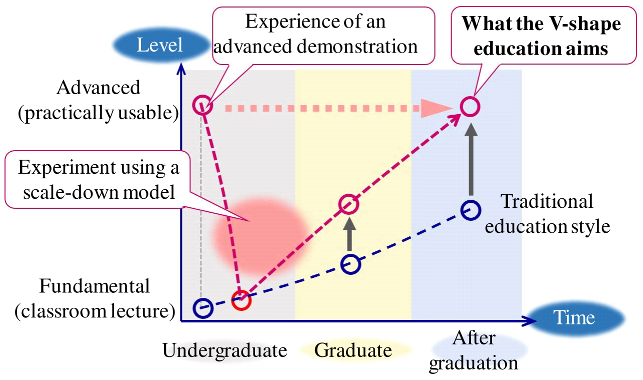


FIGURE 1. Flow chart of the V-shape education style.

for research purposes. Classroom lectures in which learning materials previously explored for students and they work on are called a flipped classroom [3], [4]. In a blended learning style, online digital learning media is used with traditional classroom methods in combination [5]–[8]. A previous study experimentally demonstrated the blended learning style [9]. These two approaches have similar characteristics in that both approaches provide teaching materials outside of the classroom. Reference [10] proposed to use student-generated videos for an effective lab-based teaching style. The video making process would encourage students to learn their own topics. In addition, using outside activities and well-designed classroom lectures created better learning experiences and enhanced students' motivation [11].

We propose a lecture style referred to as the "V-shape education style." An execution flow chart for the V-shape education style is shown in Fig. 1. Unlike traditional teaching styles in which the content level is gradually developed, thus drawing an upward learning curve, the V-shape education style includes an advanced demonstration of a given technology at the very beginning of a lecture. Students observe one of the largest/significant experiments first hand and also learn its academic background. The experience motivates students to learn more in subsequent lectures and accelerates their knowledge. Knowing one of the most advanced applications of the technology at the beginning of the learning phase has much better prospects than the traditional teaching style. In educational fields, providing a chance for students to experience a demonstration of an advanced technology at the beginning of the curriculum can be possible. One of the important points of the V-shape education style is the enhancement of students' learning by the interaction between educational materials. Not only providing the demonstration of the technique, numerical simulation examples, classroom lectures, and other educational materials are also provided to detail the academic background of the demonstration on the same day. These contents are strongly associated with each other and the synergetic effect boosts students' motivation and skill. Besides, the V-shape education style provides a scale-down model experiment on the advanced demonstration. In the traditional teaching style, the first opportunity for students to use what they have learned would be in their graduate work or profession. Providing the experiment at an appropriate timing, the students' work is supported. Students use an experimental device to review what they experienced and learned during the demonstration. Besides, another algorithm is also installed into the device. Conducting complex experiments that can not be demonstrated on the larger experiments, students develop skills using the hardware and software; these tools can be synchronized or connected to computers and external devices, such as actuators, sensors, and user-interface elements. We expect that by offering a V-shape education-based curriculum for students, they can develop better skills than their peers. The scale-down experiment using the model device supports students in understanding what they learned through the large-scale experiment. In addition, students use what they learned for more advanced experiments on the device to develop their practical skills.

This paper explains a lecture set to profile the use of a vibration engineering lecture based on the V-shape education style launched in 2015 [12], [13]. To investigate the effectiveness of the proposed lecture style and students' impressions, we launched the V-shape based lecture plan within the officially sanctioned curriculum of our university. An education flow chart based on the V-shape education style that employs dual-scale experiments is shown in Fig. 2. As a large-scale demonstration of an advanced technology, students experience the free vibration experiment of an actual seismic building as a part of their "vibration engineering: lecture and exercise" class in their second-year of undergraduate engineering course. The Disaster Mitigation Research Building (Gensai-kan) offers the public enlightenment and education for disaster mitigation. The free vibration experiment of the building, numerical simulator for the experiment, and several experience-based educational materials are strongly associated with each other and can provide students unparalleled experience, which is what the V-shape education style wants to achieve. After two years, some of the students conducted a scale-down experiment using an experimental device as a part of the "optimal control theory" class in their fourth-year of undergraduate studies. Not only recreating the free vibration experiment on the seismic building, but the device also offers an active vibration control experiment for students. Since the optimal control theory is the selective subjects, the number of students is usually smaller than that of students who attended the lecture in the actual building. Moreover, this subject is offered for fourth-year students and thus there is a two years interval between the two experiments. Since there were limitations in arrangements of the subject caused by the undergraduate engineering course curriculum, this was an inevitable problem. In this paper, we used the characteristics of the lecture with a relatively small number of students to take a carefully prepared questionnaire to know how the students assess the timing to offer the lecture, useful aspects of the lecture, and so on. The results can be used to improve the V-shape based curriculum, including the timing to offer the second experiment. In our previous paper in

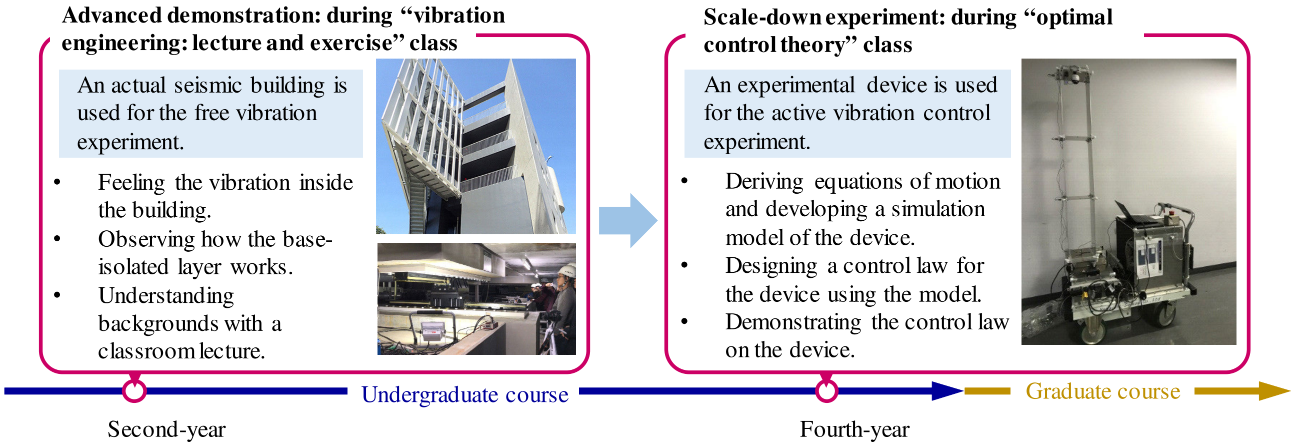


FIGURE 2. Education flowchart employing dual-scale experiments in combination.

proceedings of the IEEE Frontiers In Education Conference 2018 [14], we reported the large-scale experiment in 2015 and scale-down experiment in 2017. Additionally, this paper also reported the large-scale experiment in 2016 and scale-down experiment in 2018. The overall effects of the education style for vibration engineering on the results are described based on more compelling data.

The remainder of this paper is organized as follows: In section II, we describe a free vibration experiment offered in 2015 and 2016. In addition to the details of the lecture using an actual seismic building, the results of the questionnaire are provided and discussed. Section III describes scale-down experiments using an experimental device. We briefly review the experimental device and provide a mathematical model for numerical simulations. Besides, the virtual reality systems that offer students a visually rich learning experience are also described. The details of the lecture using the experimental device are reported in section IV. Based on the questionnaire results, the effectiveness of the proposed education style is discussed. In section V, we conclude this paper with a summary and brief discussion.

II. FREE VIBRATION EXPERIMENT USING AN ACTUAL SEISMIC BUILDING

A. OVERVIEW

The first trial of the vibration engineering lecture based on the V-shape education style was demonstrated in 2015. The seismic building shown in Fig. 3 was used for the experiment [15]. The building is five stories high and weighs approximately 6,100 ton. It has a base-isolated layer composed of laminated rubber bearings, oil dampers, and cross-linear bearings. By using the isolation mechanism, the building can handle maximum level of earthquake shaking which is expected at the site. Besides, free vibration experiments on the building can be conducted with oil jack loading systems in the base-isolated layer. Gensai-kan is, as mentioned in the previous section, the only seismic building that can handle enlightenment and education for disaster

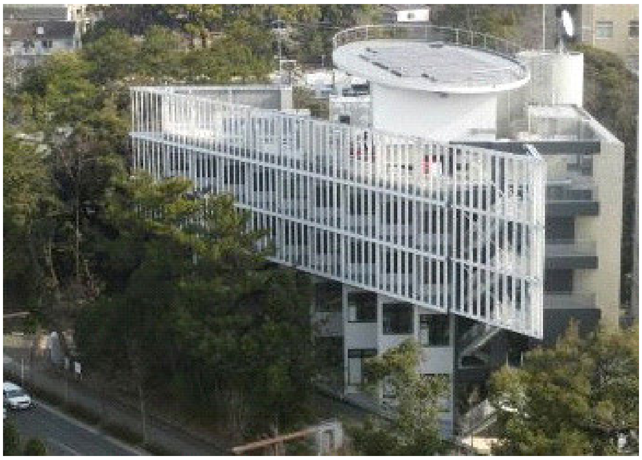


FIGURE 3. Outside view of the seismic building used for the free vibration experiment [15].

mitigation and thus can be useful for developing the V-shape education style-based curriculum. Examples of displacement responses of the experiment are shown in Fig. 4 [12]. Without oil dampers, the building becomes an underdamped system, and the vibration gradually tapers off to zero (dashed line in Fig. 4). With oil dampers, the building becomes a critically damped system (solid line in Fig. 4). In both cases, the displacements were around 90 mm. For safety reasons, students experienced the vibration of this critically damped system.

At present, the lecture is offered to all the second-year students in the mechanical and aerospace engineering courses. The number of students who attended the lecture was approximately two hundreds. Students were divided into two groups: one witnessed first-hand how the isolation mechanism works, and the other felt the artificial free vibration inside the building. The two groups alternated roles and all students experienced the vibration both ways. Fig. 5 is a photo of the base-isolated layer from the experience-based lecture in 2015. On the same day, there was a classroom lecture inside the building that explained more about the experiment.

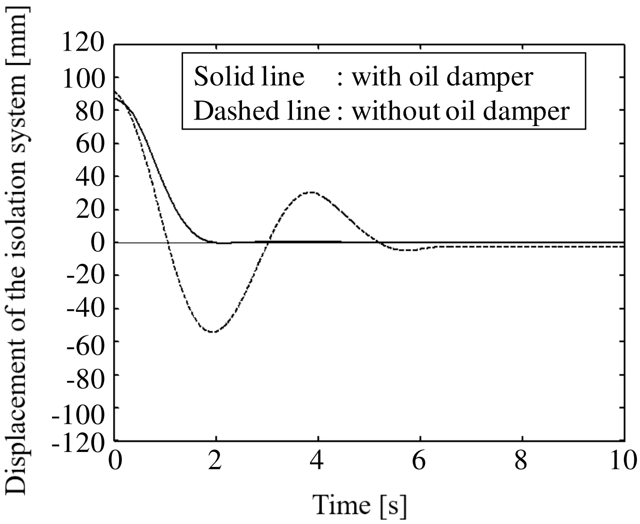


FIGURE 4. Examples of displacement responses [12].

FIGURE 5. Observation of the base-isolated layer of the seismic building.

During the lecture, the experiment's academic background was explained and the experiment was numerically simulated. Besides, through the explanation of the passive vibration control of the building, the contents of the lecture got further into the control engineering in a short time. Questionnaires were also distributed to investigate how the experiment was received by the students and gather suggestions for improvements.

B. QUESTIONNAIRE RESULTS

Student's impressions of the lecture are illustrated in Fig. 6 for 2015 and 2016. The result indicates that 97.7% of the students positively reacted to the lecture in 2015. In particular, 59.8% of the students assessed the experiment as very useful. Besides, 37.9% of the students assessed the experiment as being moderately useful. Although the percentage of the students who assessed the lecture as very or moderately useful slightly changed in 2016, the lecture was favorably received too. Around 2% of the students responded as neither useful nor poor in both years, and nobody answered that the experiment was poor. Table 1 summarizes the students' descriptions of why they assessed the experiment as (very

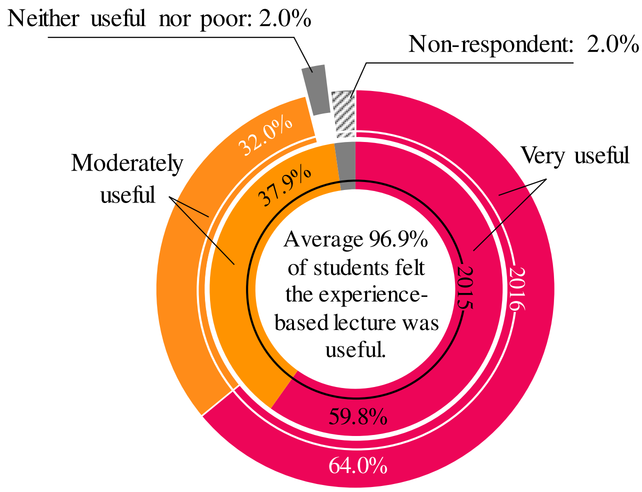


FIGURE 6. Did you find the experience-based lecture on free vibration using the seismic building useful?.

TABLE 1. What aspects of lecture using the actual seismic building did you find useful? (select all responses that apply to you).

	2016	2015
Experiences that cannot be obtained in typical classroom lectures were good.	54.2%	79.3%
The ability to generate interest in earthquakes, disaster mitigation, and architecture was good.	62.5%	52.9%
The ability to generate interest in vibration engineering was good.	47.9%	37.9%
The experiment experience was better than the items on the Internet, such as videos.	29.2%	28.7%
The lecture may help us to understand what we have learned during typical classroom lectures.	12.5%	28.7%
The combination of the experience, numerical simulations, and classroom lecture was good.	12.5%	21.8%

or moderately) useful for 2015 and 2016. In 2015, 79.3% of the students answered that the experience that cannot obtain through typical classroom lectures was good. In 2016, smaller 54.2% of the students choose this point, but still high. Since the seismic building is the facility in which disasters are simulated, 52.9% of the students became interested in earthquakes, disaster mitigation, and architecture in 2015. In 2016, 10% larger 62.5% of the students assessed this point. Besides, 37.9% of the students felt that they developed an interest in vibration engineering. Although most of the students favorably reacted to the experiment, a relatively small number of the students thought that it had a particular advantage over items found on the Internet like photos or videos. Further, only a small percentage of students (28.7% in 2015 and 12.5% in 2016) thought that the experiment helped them understand what they learned in typical classroom lectures. It can be related to the content balance of

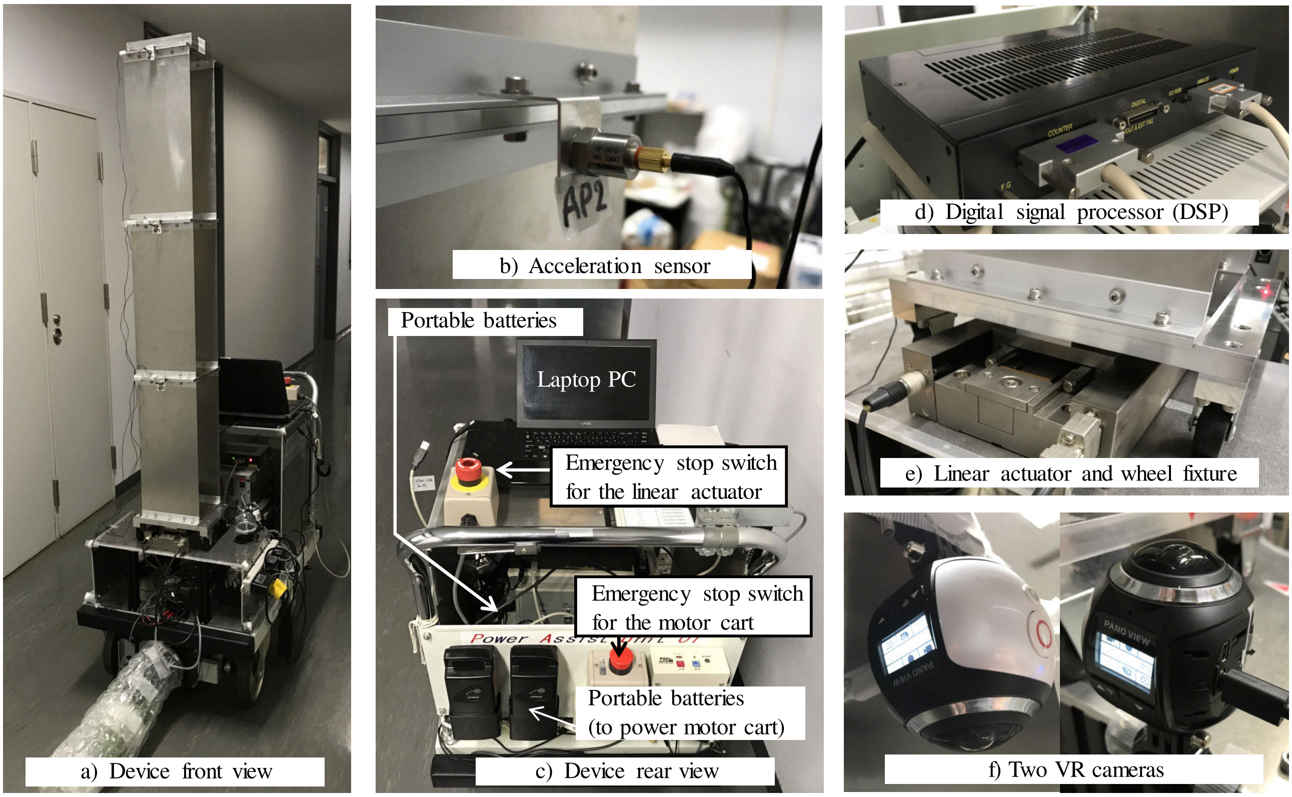


FIGURE 7. Image of the scale-down experimental device.

the lecture. The 90-minute lecture included the large-scale experiment, numerical simulation, and classroom discussion; there may be room for improvement in the content balance. Students who assessed providing several materials were only 21.8% in 2015 and 12.5% in 2016, respectively. Introducing several items during a lecture to motivate students is not uncommon these days [16], [17]; therefore, few students valued this factor. Overall, though there were small changes between the results of 2015 and 2016, the tendency was not so changed depending on the generations. Besides, we had several comments on the lecture from students. As far as the comments showed, a significant difference between the two groups was not observed. As the results showed, students who attended the experience-based lectures reacted positively in both years. The lecture style has been improving for four years.

III. DEVELOPMENT OF AN EXPERIMENTAL DEVICE AND LECTURE PLAN

As described in section I, the V-shape education-based curriculum provides an experiment that uses a scale-down model of a large-scale experiment. Here, an experimental device and lecture plan developed for an effective scale-down model experiment are described.

A. DEVICE OVERVIEW

Fig. 7 is an experimental device that we developed in 2017. As Fig. 7 a) shows, the device comprises of a vibration component and motor cart. The vibration component accounts for the seismic building, and the motor cart accounts for the ground, respectively. They are connected to a linear actuator that exerts a force on the vibration component. The linear actuator accounts for the base-isolated layer of the seismic building. During the experiment, the device is manually shaken using the handle mounted on the motor cart.

The vibration component is a single bay several-story frame with columns of equal firmness at the side (blade springs). The blade springs are made of aluminum with an average cross section of 2.0 mm by 200 mm the floors are also made of aluminum plates that are attached to the springs. A bay is fixed to the other floor using bolts and nuts, and the number of stories can be easily varied as per requirements. The horizontal component of the floor acceleration is detected by an acceleration sensor that is mounted on each floor. For example, the acceleration sensor for the second floor is shown in Fig. 7b). We also prepared additional weights made of aluminum to change the mass of each floor. Due to the limited space of the lecture room, the vibration component was set to be three-story. Besides, only the weight of the roof was changed (details provided in the device parameters in section III-B). Fig. 7c) is the rear view of the device. It has two emergency stop switches, one is to stop the linear actuator, and the other is to stop the motor cart. As in Fig. 7c), the motor cart has a separate power supply to conduct the experiment anywhere. An assist system to aid the experimenter is powered by portable batteries used with electrically-assisted bikes. The human force is sensed by strain gauges mounted on the handle, and an assistance force is calculated by the digital signal processor (DSP) and added to shake the experimental device so that little human force is needed. The laptop computer, DSP, and linear actuator are powered by portable batteries as in Fig. 7d). To take the weight load off of the linear actuator that connects the vibration component and the motor cart, as in Fig. 7e), the vibration component is mounted on a fixture with four wheels. The linear actuator exerts a force as a function of the input voltage. The actuators in the motor cart and linear actuator are controlled by the DSP. For supporting students' learning, the cart also has two virtual reality (VR) cameras (Fig. 7f). The VR technology is now widely used for entertainment [18], in industries [19], and even for educational purposes [20], [21]. The visual aspects of the VR system are expected to boost students' motivation. One VR camera is mounted on the top floor roof (the left photo of Fig. 7f). The camera is inverted and pointed on the motor cart to provide a top-down view. The other camera is mounted on the aluminum plate on the motor cart and is pointed on the vibration component so that an observer can look up the vibration. These cameras transmit real-time videos via a wireless network to the VR headgears. The students' vision is scaled down by the VR system. Instead of just observing the vibrating experimental device from outside, they can witness first-hand the vibration of the vibration component, the working of the linear actuator, and absorption of the vibration. The experiment is conducted by a team of three students: one device operator and two observers. The system provides a virtual building vibration experience. It motivates students even if free vibration experiment with the actual seismic building is not possible. Also, the VR system was constructed by commercially available cameras and smart phones, and thus it is simple to install.

B. MATHEMATICAL MODEL AND CONTROL METHOD

The mathematical model for the device with the n-story vibration components is illustrated in Fig. 8. The equations of motion to calculate the behavior of the vibration component are given by

$$\ddot{x}_i = \frac{k_{i+1}}{m_i}x_{i+1} + \frac{c_{i+1}}{m_i}\dot{x}_{i+1} - (k_i + k_{i+1})\frac{x_i}{m_i} - (c_i + c_{i+1})\frac{\dot{x}_i}{m_i} + \frac{k_i}{m_i}x_{i-1} + \frac{c_i}{m_i}\dot{x}_{i-1}, \quad (1)$$

$$\ddot{x}_n = -\frac{k_n}{m_n}x_n - \frac{c_n}{m_n}\dot{x}_n + \frac{k_n}{m_n}x_{n-1} + \frac{c_n}{m_n}\dot{x}_{n-1}, \quad (2)$$

$$\ddot{x}_a = (k_1x_1 + c_1\dot{x}_1 - k_1x_a - c_1\dot{x}_a + K_ae_a - f_w)/m_a, \quad (3)$$

$$\ddot{x}_b = (F_h + F_c + f_w - f_c)/m_b \quad (4)$$

where x_i is the displacement of the i-th floor; x_a is the linear actuator displacement; x_b is the motor cart displacement; k_i, c_i, and m_i are the spring coefficient, damping coefficient, and mass of the i-th story, respectively, K_a is a thrust constant of the linear actuator, e_a is an input voltage for the linear actuator, F_h is the human force, F_c is the motor cart's assist force, f_w is the Coulomb friction force exerted on the linear actuator, and f_c is the Coulomb friction of the motor cart wheel. The device parameters are summarized in table 2. A block diagram, that explains the control system of the device, is shown in Fig. 9. Note that $x_c = [x_b, \dot{x}_b]$ is the state vector of the motor cart, $x_v = [x_1, \dot{x}_1, \cdots, \dot{x}_a]$ is the state vector of the vibration component, A_v is the state matrix of the vibration component, and f_b^* and f_b are the feedback gains of active and passive control, respectively. To support the experiment, an impedance control theory that assists human force F_h to shake the cart, reaction force controller, and disturbance observer for a noise reduction are implemented. The operation of the linear actuator is based on a generated force that is related to the input voltage. The input voltage is determined so that the force minimizes a given floor's velocity relative to the linear actuator. Since the scale-down experiment is conducted during the ''optimal control theory'' lecture, the strategy to determine the input voltage should be adjusted to suit the lecture.

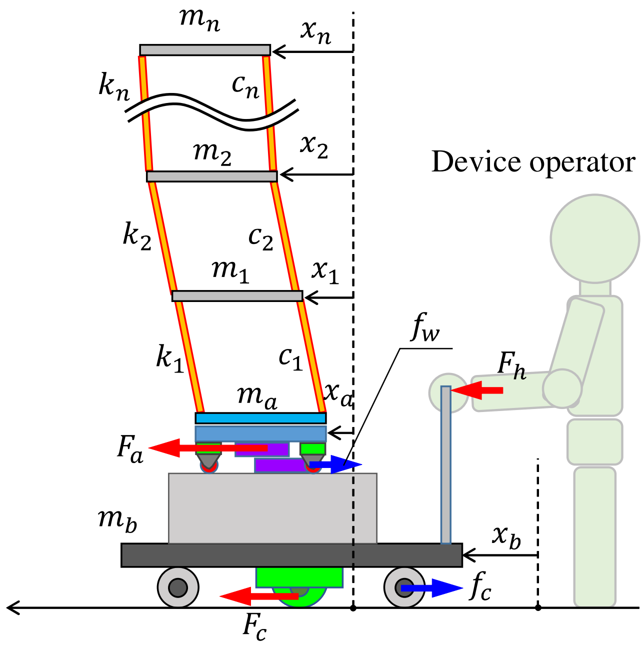


FIGURE 8. Mathematical model of the scale-down experimental device.

TABLE 2. Physical parameters of the experimental device.

Parameter	Value
m_i $(i = 1, \cdots, n-1)$	2.01 kg
m_n	3.52 kg
m_a	5.82 kg
k_i $(i = 1, \cdots, n)$	2.28×10^3 N/m
c_i $(i = 1, \cdots, n)$	1.50 Ns/m
K_a	2.51 N/V
f_c	35.0 N
M	133.2 kg

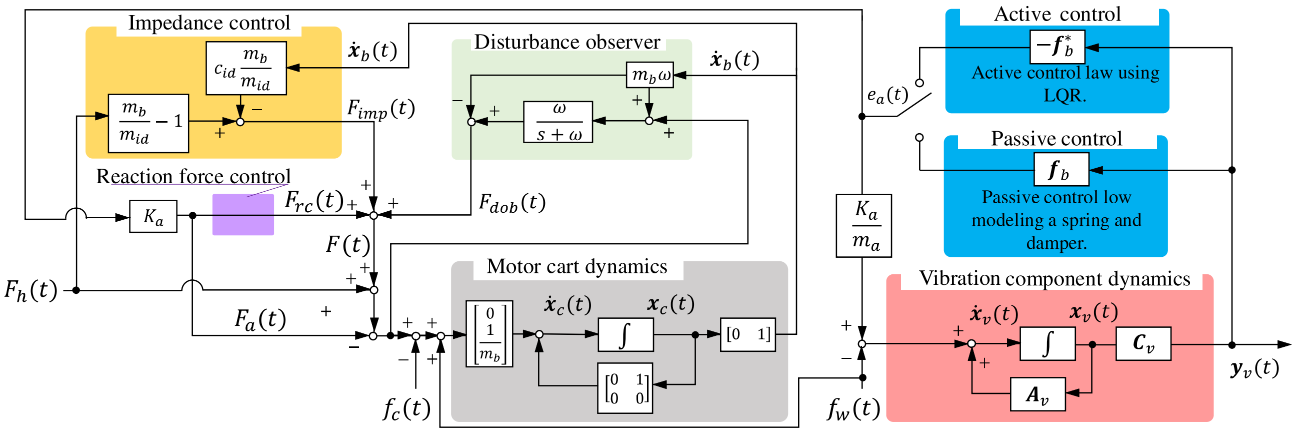


FIGURE 9. Block diagram of the control system.

C. LECTURE PLANNING

We describe the design of the lecture using the experimental device. The lecture is conducted as a part of the optimal control theory classes for fourth-year students. It is desired that the lecture can deal with the room for improvement found during the large-scale experiment. Few participants answered that the free vibration experiment helped them understand typical lectures (28.7% in 2015 and 12.5% in 2016). To address this response, we proposed two-day lectures to qualitatively and quantitatively enhance the content. The first day is an experience-based classroom lecture: students learn the academic background and conduct numerical simulations for the scale-down experiment. On the second day, students conduct an active vibration control experiment using the device. To attract students' interests, the VR system is used for the experiment on the second day.

On the first day the students learn the fundamental background, programming skills, and designing of the controller. Students briefly review the free vibration experiments on the actual seismic building to recall what they experienced and learned two years ago. After a brief review, students derive the experimental device's equations of motion ((2)–(4) in section III-B) to understand the device better. Besides, they learn how to model the free vibration experiment using the scaled-down experimental device. By using the linear actuator, an oil damper and rubber bearing are modeled as a damper and spring, respectively. Students also watched videos of the free vibration experiment recreated by the device. At the end of the first day, students prepare for the active vibration control conducted during the second lecture day. The principle of vibration control using a linear quadratic regulator (LQR) is also explained. A cost function J of the LQR is given by

$$J = \int_0^\infty (x^T Qx + re_a^2)dt \tag{5}$$

By using a numerical simulation tool provided by the instructor, students try to design the matrix Q so that the acceleration of the vibration component is minimized. For simulations, we use $r = 1$. The state vector for the system is $x = [x_1, \dot{x}_1, \cdots, x_b, \dot{x}_b]$. Students follow the provided clues and simulated the device behavior using several types of Q. Consider the following as an example of the matrix for three story vibration component Q:

$$Q = \left(\begin{array}{c|ccccc} 0_{5\times5} & & & 0_{5\times5} & & \\ \hline & q_v & 0 & -q_v & 0 & 0 \\ & 0 & q_p & 0 & -q_p & 0 \\ 0_{5\times5} & -q_v & 0 & q_v & 0 & 0 \\ & 0 & -q_p & 0 & q_p & 0 \\ & 0 & 0 & 0 & 0 & 0 \end{array}\right) \tag{6}$$

Equation (6) leads $x^T Qx = q_p(x_a - x_b)^2 + q_v(\dot{x}_3 - \dot{x}_a)^2$ that minimizes the displacement between the linear actuator and the motor cart, and the difference between the velocities of the third roof and the linear actuator. Not to violates the limitation in the stroke of the linear actuator, the importance of the first term $q_p(x_a - x_b)^2$ is also described to students. After the first day, students will develop the necessary background required for the second day's experiment. Because the students learned about the LQR in the optimal control theory classes a few weeks prior to the lecture, adopting the LQR might facilitate their understanding.

The second day mainly focuses on experiments using the device. After a quick review of the first day's lecture, students form small groups and conduct the experiment. The group consists of three students: one device operator who shakes the motor cart, and two observers who use the VR equipment to note the working of the LQR absorbing the vibration. Students also observe the behavior when the control law is not installed and investigate the differences. Students alternate roles throughout the experiment. Besides, a real-time video of the base-isolated layer is also taken by a small camera mounted on the linear actuator and displayed on a large screen in the classroom. At the end of the lecture, students are required to answer questionnaires for review and feedback.

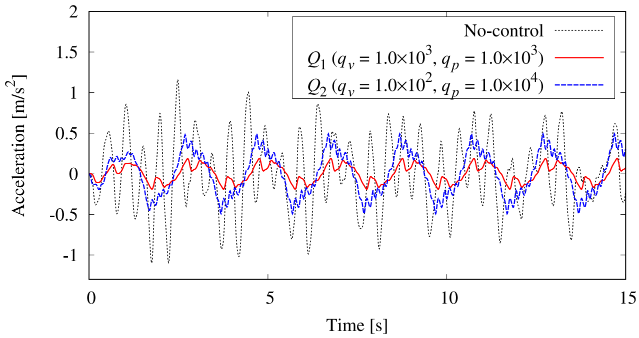


FIGURE 10. Time histories of the change in the third floor acceleration.

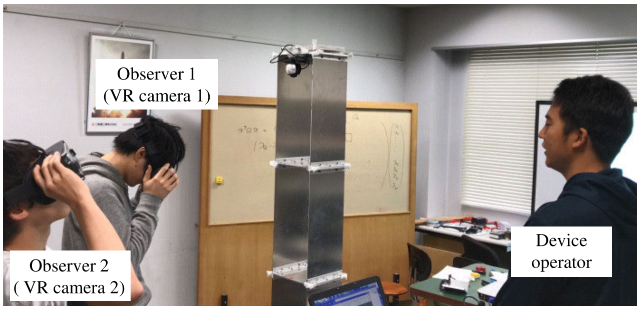


FIGURE 11. Experiment on the second day lecture (2017).

IV. LECTURE AND QUESTIONNAIRE RESULTS

Approximately twenty fourth-year students attended the lecture, which represents 10% of the students who experienced the free vibration experiment in 2015 and 2016. Collecting opinions from students who attended the free vibration experiments helped investigate the effectiveness of the lectures that employed the V-shape education style. As planned, during the first lecture, students reviewed the academic backgrounds and designed the LQR controller using the simulation tool. We prepared tools written in Fortran 90 and MATLAB®, and students used the latter. Students changed the value of the weight matrix components q_p and p_v in the weight matrix Q, and calculated the acceleration. Fig. 10 shows accelerations of the vibration component that were simulated using the provided tool. The motion of the vibration component was numerically solved and the accelerations of the third floor were shown. During the second lecture, as in Fig. 11, students independently performed the experiment. One group spent approximately 5 min to conduct the experiment. The others observed the experiment from outside or checked the real-time video recorded using the other USB connection camera that was mounted under the wheel fixture of the vibration component. The students' impressions were investigated through the following questionnaires. In this paper, we focus on whether the lecture was positively received or not by students and aspects where the students assessed as useful. First, we investigate the overall success by asking whether the students assessed the lecture as useful or not. In addition, deeper questions to investigate aspects where the students assessed as useful follow. In the latter questions, students can select all options that apply to them.

A. ATTAINMENT LEVEL OF THE DESIRED GENERAL OBJECTIVES BASED ON THE STUDENTS' IMPRESSIONS

We asked the following three questions to investigate whether the desired general objectives were achieved:

a) Did you find the lecture employing the experimental device useful?
b) How did it feel to observe the experiment using the VR system?
c) Did you find the lecture approach that combined the dual-scale experiments to be useful?

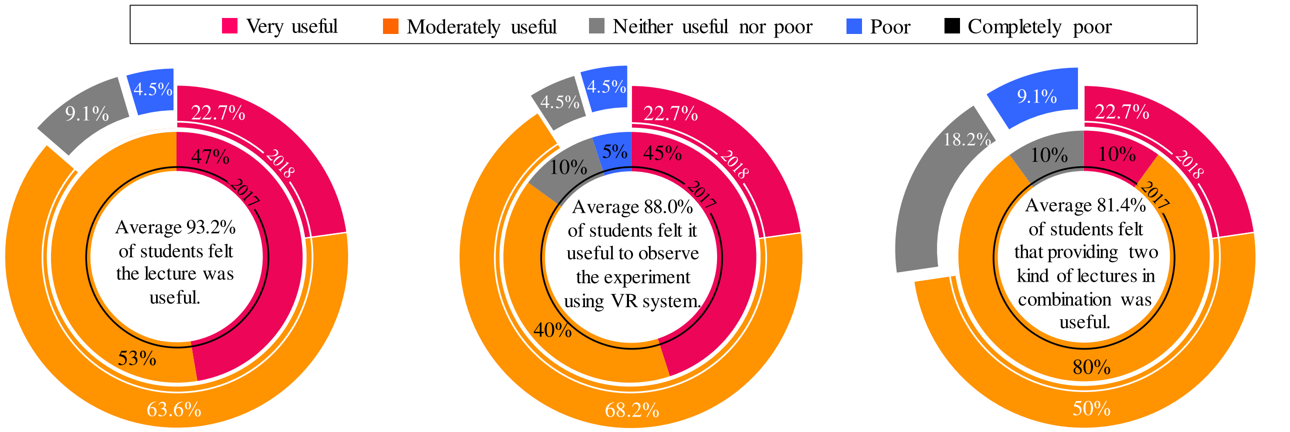
The options were as follows:

- ▶ Very useful
- ▶ Moderately useful
- ▶ Neither useful nor poor
- ▶ Poor
- ▶ Completely poor

Students' responses to the questions a)–c) are summarized in Fig. 12. The red areas (47% in 2017 and 22.7% in 2018) in Fig. 12 a) represent the percentage of students who assessed the lecture as very useful. The orange areas (53% in 2017 and 63.6% in 2018) represent the percentage of students who assessed the lecture as moderately useful. As the result shows, the lecture was positively received by all students in 2017. In 2018, 9.1% of the students found the lecture to be neither useful nor poor. Though 4.5% of the students answered that the lectures were poor, many students still valued the lecture as useful (86.3%). Fig. 12 b) indicates how students felt about observing the experiment using the VR system. As in Fig. 12 b), 45% of the students assessed the VR system as very useful, and 40% assessed it as moderately useful in 2017. In 2018, more students reacted to the VR system positively as in Fig. 12 b). Though only a small percentage of students selected very useful (22.7%), 68.2% of the students valued the VR system as moderately useful. The VR system was more or less positively received by students for both years. Fig. 12 c) indicates how students felt about lectures where both the seismic building and experimental device were used together. Overall, 90% of the students assessed providing dual-scale experiments in combination as very (10%) or moderately (80%) useful in 2017. In 2018, however, 18.2% of the students felt that the combination as neither useful nor poor and 9.1% chose poor. Therefore, the positive opinion was decreased to 72.7%. These three results for 2017 and 2018 indicate that the lectures' desired objectives were achieved. However, a method to make the students understand the relationship between dual-scale experiments is yet to be developed.

B. USEFUL AND POOR ASPECTS OF THE LECTURE

The aspects of the lecture that students valued as useful are listed in table 3. The answers have been curated according to the rating obtained for 2017. Note that students selected all options that applied to them. As table 3 indicates, approximately 65% (63.2% in 2017 and 68.4% in 2018) of the students felt this to be an educational experience that cannot be obtained during typical classroom lectures. Besides, 42.1% of the students answered that the experiment was better than



a) Did you find the lecture using the experimental device useful?

b) How did you feel to observe the experiment using VR?

c) Did you find the lecture approach that combined the actual seismic building and experimental device to be useful?

FIGURE 12. Questionnaire summary.

TABLE 3. What aspects of the lecture using the experimental device did you find useful? (select all that apply to you).

	2018	2017
Experiences that cannot be obtained through typical lectures were good.	68.4%	63.2%
The experiment experience was better than educational resources found on the Internet, such as videos or photos.	42.1%	42.1%
The ability to gain interest in control engineering was good.	42.1%	36.8%
The combination of the experience, numerical simulation, and classroom lectures was good.	15.8%	36.8%
The lecture helped us understand what we learned in typical lectures.	5.3%	26.3%
The ability to gain interest in vibration engineering was good.	0%	15.8%

educational resources found on the Internet, such as videos or photos for both years. Introducing experiments and simulations into a classroom lecture is more common today, and 36.8% of the students assessed the combination of several materials in 2017. A similar tendency was observed in 2018 (15.8%). Meanwhile, 26.3% of the students thought that the lecture helped them understand the content of typical classroom lectures in 2017. Compared with 2017, this point was not so valued in 2018 (5.3%). In addition, there were large differences between the number of students who developed an interest in control engineering (36.8% in 2017 and 42.1% in 2018) and vibration engineering (15.2% in 2017 and 0% in 2018). The lectures were held during the last two optimal control theory sessions at our university. Besides, the students learned about the LQR in preceding sessions, and even on the first day. The knowledge of the LQR could work as an unconscious bias and students might not be aware of the

TABLE 4. Why was it useful to use the VR system? (select all options that apply to you).

	2018	2017
The VR system provided a view as if one was inside the device.	55%	58.8%
I felt the device vibration using the VR system.	65%	52.9%
The VR system itself is attractive to me.	0%	47.1%
I felt how the control law worked.	25%	23.5%
Observing the experiment using the VR system helped us understand typical classroom lectures.	20%	11.8%

lecture's vibration engineering aspects. In 2018, one student felt that the lecture was poor. We also prepared options for students who value the lecture as poor. The student felt that the scale-down experiment was unnecessary, because photos and videos are enough to learn the academic background of the vibration control.

C. USEFUL AND POOR POINTS OF VR SYSTEM

The aspects that students found that the VR system was useful are listed in table 4. Note that students whose previous response to the question c) was very or moderately useful also answered this question. Fortunately, more than 50% (58.8% in 2017 and 55% in 2018) of the students assessed the sight scaled-down by the VR system. Overall, 52.9% of the students felt that the VR system helped them feel the device vibration in 2017. In 2018, this opinion was improved to a maximum of 65.0%. Though approximately half of the students in 2017 valued the VR system itself, nobody selected this option in 2018. Overall, approximately 25% (23.5% in 2017 and 25.0% in 2018) of the students thought that the system was useful to observe how the control law works.

In 2017, only 11.8% of students thought that the system helped them understand typical classroom lectures; however, it was improved to 20.0% in 2018. Evidently, the results reflect that the visual impression created by the VR system did not considerably improve students' understanding of the experiment's academic background.

A reason the VR system's visual aspects were highlighted might depend on whether the students were accustomed to using VR products. For both years, only one student responded that they frequently used some type of VR products. Overall, 35% of the students have used VR products, while 60% have never used them in 2017. Fewer students in 2018 used the VR system; 22.7% of them responded that they have used some type of VR product, 72.7% never used any. Because approximately 85% of students were not accustomed to using VR products for both years, they might select options that reflect the VR system's visual aspects.

We also asked students whether the VR video quality was appropriate for the lecture. In the lecture, to observe the experiment in real-time, low-quality VR videos were shown. Meanwhile, if the real-time observation was excluded, we can record high-quality VR videos beforehand and play them during lectures. The students' responses indicated that most students (85% in 2017 and 86.3% in 2018) agreed with providing real-time, low-quality videos. Besides, approximately 25% of the students were also satisfied with the video quality. Meanwhile, approximately 60% of the students did not like the low-quality video, however, stated that providing real-time videos were more important. Meanwhile, approximately 10% (10% in 2017 and 13.6% in 2018) of the students answered that it would be better to watch pre-recorded, high-quality videos using the VR system. 5% of the students who felt using the VR system as poor in 2017 thought that it was difficult to feel the device's vibration. Since 4.5% of the students felt that using a large screen is better to show the device's vibration, the student thought the VR system poor in 2018. Though we had a small number of negative responses, the questionnaire results indicated that the students favorably reacted to observe the experiment in real time with the VR system. In addition, providing high quality prerecorded VR videos of the experiment can effective in some cases. As we mentioned, the experimental device enables us to conduct the vibration control experiment without using an actual seismic building. Since the VR system in this paper uses only easily available products, introducing the prerecorded VR videos into typical classroom lectures is much easier.

D. USEFUL AND POOR ASPECTS OF THE COMBINATION OF DUAL SCALE EXPERIMENTS

Table 5 lists the students' responses as to why they found the combination of the dual-scale experiments useful. For both years, students valued that the dual-scale experiments helped them better understand the mechanism of the base-isolated layer (50% in 2017 and 38.9% in 2018). Approximately 30% (27.8% in 2017 and 31.3% in 2018) of the students could understand the seismic mechanism during the experiment and the model experiment was useful for them to check what they learned two years ago. 27.8% of the students responded that the experiment using the seismic building was not enough to understand the academic background of the lecture and the model experiment helped them understand it. In 2018, the percentage of students who chose this option decreased to 12.5%. For both years, approximately 25% (22.2% in 2017 and 25% in 2018) of the students responded that they forgot about the experiment conducted two years ago and that they could remember and check its academic background during the model experiment. In addition to experiencing the building shake two years ago, the students learned the academic background of the isolation mechanism via a mathematical model of the experimental device, numerical simulation, and model experiment during the lecture. As the results indicate, the combination of the dual-scale experiments is a good educational material for students who have various levels of understanding. In 2018, on the other hand, 9.1% of the students valued the combination as poor. One student could not understand the free vibration experiment in two years ago, and could not understand the scale-down experiment. The other student felt that the large-scale experiment was not good for understanding academic background well, and thus the combination was also poor (in the free description).

TABLE 5. What aspects of the combination of the dual-scale experiments did you find useful? (select all that apply to you).

	2018	2017
Dual-scale experiments were useful to better understand the mechanism of the base-isolated layer using springs and dampers.	50%	38.9%
The model experiment was helpful to check what the students understood during the experiment using the seismic building.	31.3%	27.8%
I could not fully understand the mechanism of the seismic building two years ago; however, the model experiment helped me understand it.	12.5%	27.8%
I forgot about the experiment; however, the model experiment helped me understand the seismic mechanism.	25%	22.2%

E. COMPREHENSION LEVEL CHECK TEST

The questionnaire results in 2017 indicated that the lecture style employing dual-scale experiments is effective to motivate students' learning. In 2018, we also investigated how the lecture style affects the students' comprehension level. To this end, we took two questions for the questionnaires in 2018. The questions were:

- Q. 1: If we changed the damping coefficient of the damper modeled by the linear actuator, how the behavior of the vibration component changes? Especially, if the damping coefficient is zero, how the component behaves?

- Q. 2: If we use a vibration component with thinner aluminum blade spring, how the behavior of the component changes?

The first question accounts for changing the parameters of the base-isolated layer of the seismic building at the free vibration experiment. In the first day of the lecture, students observed the experiment that models the free vibration of the seismic building. In the experiment, the control law was selected so that the linear actuator behaves as if it is composed of a spring and damper. In the first day of the lecture, students reviewed seismic building. In the lecture, the difference of the damping coefficient was also explained. Besides, we demonstrated the case in which the damping coefficient was zero in the second day, Q. 1 should be easy to answer. The Q. 2 is about the change in the parameter of the vibration component. The higher order vibrations were not mentioned in the lecture on the first day. As long as we use the three-story vibration component, first order vibration mode is mainly observed in both simulation and scale-down experiment. Note that the students answered the questions in freedom description style.

For the Q. 1, we had nineteen answers. 84% of the students mentioned the change in the vibration behavior of the component. The number of students who described the change in the vibration using technical terms was only three, in spite that the terms were described in the first day. The result shows that they can understand the difference in the behavior of the vibration component caused by the performance of the base-isolated layer. During the first day's lecture, they derived the equations of motion for the experimental device. Besides, by solving the equations with the numerical simulator, they indirectly experienced to change the parameters for the linear actuator by themselves. What they did by themselves was preferentially memorized. For Q. 2, we have twenty one answers. Four students mentioned that higher-order vibration mode can be observed. Students who mentioned the higher-order vibrations could connect their own knowledge to the lectures. As unintended answer, six students mentioned the buckling of the aluminum plates. These are not incorrect answers but seem facile. The Q. 2 should be an induction question style.

F. TIMING TO PROVIDE THE LECTURE USING THE EXPERIMENTAL DEVICE

The timing to provide the lecture using the scale-down model was also investigated as the final question. The options were as follows:

- Optimal
- During second-year, but after the experiment with the seismic building
- Before the experiment with the seismic building
- During third-year
- We don't need the lecture

The students' responses are summarized in Fig. 13. In 2017, 10% of students thought that the timing to offer the lecture

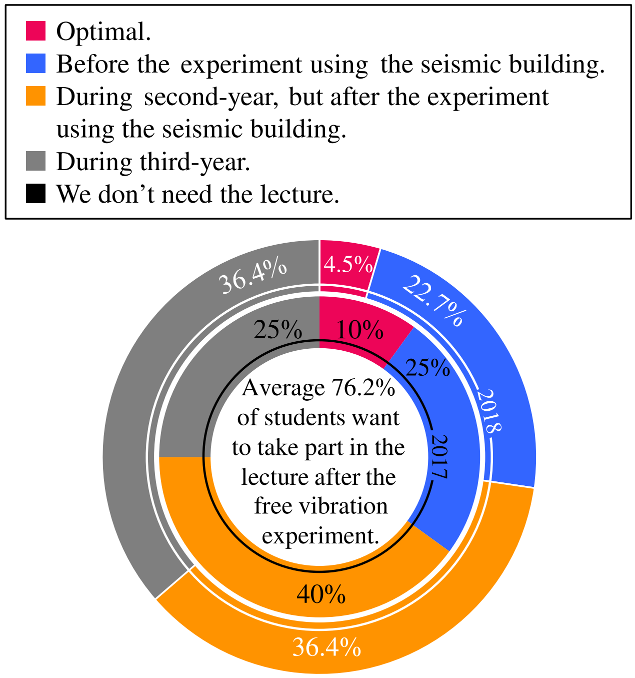


FIGURE 13. What is the appropriate timing for students to attend the lecture using the experimental device?.

was optimal. Meanwhile, 40% of the students felt that the lecture should be offered during the second-year, after the free vibration experiment using the seismic building. Besides, of the students who responded, 25% answered that the lecture should be provided during the third-year. As is clear from the results, to varying degrees, 75% of students thought it would be better to offer the lecture after the free vibration experiment. In particular, 65% of the students felt that it is better to move up the timing to offer the lecture. Shortening the time required for the reviewing process we introduced into the lecture can be effective. Students can strongly associate their experiences in the actual building with the practical skills to operate the device. However, as Fig. 13 shows, 25% of students, this rate seems high, answered that the lecture should be provided before the free vibration experiment. Because the intent of the V-shape education style is to support or enhance students' learning by providing a scale-down experiment after experiencing a large-scale demonstration; this is an unintended result.

A similar tendency was observed in 2018 as in Fig. 13. The students who thought the timing to offer the lecture was optimal was 4.5%. Compared with the results in 2017, it was decreased by 5.5%. Meanwhile, 36.4% of the students preferred during the second-year, and 36.4% preferred during third-year, respectively. The results show that 77.3% of the students thought that offering the lecture after the free vibration experiment is better. Similar to the result in 2017, 22.7% of the students wanted to experience the lecture before the experiment using the actual seismic building. As the curriculum demonstrations based on V-shape education indicated, we need to optimize the lectures timing in the future.

We should at least explain to the students the purpose of the V-shape education style or the lecture.

V. DISCUSSION

A new education style called V-shape education was proposed in this paper. The V-shape education provides an advanced demonstration on a technology at the beginning of a lecture to motivate students to learn subjects. A scale-down device also supports students' motivation. Based on the V-shape education style, we designed lectures for vibration engineering and presented lectures using the free vibration of the seismic building and vibration control using the experimental device. As the questionnaire results indicated, our overall goals of the V-shape education style were achieved.

Through the present study, the framework to provide the V-shape education-based lecture has been established. We are now interested in the optimization of the lecture based on the V-shape education style. The improvements we are considering are follows:

- Strengthen the correlation between the free vibration experiment with the seismic building and the scale-down experiment.
- Enhance the correlation between the dual-scale experiments and their academic background.
- Effectively use the VR system for increasing students' interests in vibration engineering.
- Optimize the lecture duration using the experimental device.

Most students who experienced the first and second dual-scale experiments are now in the first and second years of their graduate course and have independently undertaken research. From 2020, the lectures using the experimental device is offered for third-year students. In addition, the number of students who attended the class was increased (more than 50 in 2020). The timing to offer the lecture using the device was changed as the requirement shown in the questionnaire results, and the increase in the attendee is suitable to conduct a follow-up study. By conducting a follow-up study on the changes in the students' examination score, motivation for learning, and quality of research, the effectiveness of the lecture style will be investigated. Moreover, investigations on students' careers with long-term follow up may be effective. The quality of the questionnaire survey to investigate the V-shape education style lecture can be further improved in the future.

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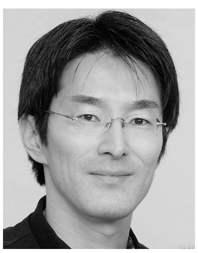

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