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ANALYSIS OF SYNTHESIS FOR REFLECTIVE LEARNING IN PROJECT-BASED DESIGN EDUCATION

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Abstract

This paper reports the intentions and experiences in introducing a new style of project-based learning for engineering design education at Department of Mechanical Engineering, Osaka University. As the engineering systems and their environments have become so complicated, the requirements on engineering education are spread from the contents of individual knowledge to the process issues for systematizing them. What is called project-based learning, in which student teams perform any design project and learn certain things from its experience, is introducing into many schools as an effective means for the latter. Our approach in this direction is characterized by the emphasis on reflection from situations realized in design projects. That is, the sequence of design, production and refinement is iterated and the overall shape of project runs are analyzed by participating students in the final phase of the course in order to enhance their reflective learning on the meaning of design problem solving and its process. Under this concept, we configure two design subjects that are fit with the limited time and space in the classroom. The first one is the design of a paper-made shock absorber that prevents deformation of a clay cone in three-meter free-fall. The second one is the design of a paper-made wind turbine for generating electricity under regulated airflow. This paper describes their regulations and observed educational outcomes after defining the conceptual style of our approach.

Keywords: *Design education, Student teams, Experiential learning.*

1 Introduction

Efficiency and depth in education are often contradictive. Since education is an essential aspect of human life, its origin must be found in one in families and local communities even though it is implicit [1]. Under social and economic development, the contents of knowledge are split into diverse subjects and education has become systematic under the school system for making it efficient. Engineering education has been typical of such a style. However, as design itself becomes a clearly indicated issue of engineering design education beyond engineering drawing, design calculation, etc., what is called project-based learning (PBL) is becoming its key component, and many engineering schools tend to introduce such pedagogy. The aim of project-based learning is to bring students real engineering experiences and teach various aspects of design methods and activities through them. It can illuminate the structure of particular design problems, but it may be still difficult to reach the deep core of design activity such as its evolutionally paradigmatic meaning.

Today's engineering design becomes so complicated to meet with contemporary technologies and demands. The above limitation of design education at schools might be reasonable due to the gap between circumstances in the classroom and the practice. However the structure of underlying incidents is made clear with two axes; contents and process. Within the trends of design engineering after 1990s, design-for-manufacturing issues, multidisciplinary design optimization, etc. relate to the former, and management issues for process innovation, etc. relate to the latter. While each of the former can be an educational subject even in undergraduate level, the latter might be postponed until, for instance, on-the-job because the latter seems to follow the former. Furthermore the process issues are tacit in some degree and evolutionary under development of content issues. This point is clarified with some concepts such as reflection-in-action, situated learning [1] and so forth. The advantage of aforementioned naive education in families and local communities can be explained by its real process where knowledge is necessary and useful. That is, real process must be an essential component for educating the whole shape including process-related issues, and the style should be one through reflective learning rather than explicit teaching. Consequently, it is necessary to bring any real design process into classrooms of design education somehow with overcoming various limitations even though practical contents are eliminated.

This paper reports our approach of project-based learning for introducing a design process in the above meaning. The second section discusses the components implemented in it, the third and fourth sections describe two developed subjects, which are used for a project-based learning class for undergraduate third-year students, and their typical outcomes. The fifth section concludes this paper with some remarks.

2 Components of a design project for reflective learning

2.1 The design process

It has become a common understanding that the design process should be organized as the sequence of planning, conceptual design, embodiment design, and detail design [2]. While the necessity of such a structure is fairly obvious in large-scale or complicated design problems, design subjects used in a classroom can often be managed without structural consideration due to their small size and simplicity. This means that it is required for students to compulsorily face the meaning of design process even under any classroom design subjects. For this purpose, clear milestones are assigned to student teams on all phases in the design process. That is, the course schedule is arranged so as that every session has a clearly specified task, and the result of students' activities in each session is checked by instructors at its end. For instance, the conceptual sketches are required to be shown at the end of the session for conceptual design. This kind of restrictions is much important for a shorter-term course for highlighting the meaning of the design process.

Beyond the above phases of the design process, production of designed devices, design review for any clients or else are a certain part of the design process in its broad sense. Thus, production is included in the course schedule as most of project-based design education is so. Design review is replaced with presentation of design intentions, etc. in front of other students.

2.2 Act-reflect-change loop

Another essential component of the design process is that iteration of various phases is essentially unavoidable and rather it is indispensable to reach better design results. On this point, while there are many arguments, Dym surveyed that design activity consists of the following design tasks: *design*, *verify*, *critique*, and *modify* [3]. Woolsey *et al.* demonstrated the importance of *act-reflect-change* loops for excellent design results [4]. These guiding principles are also very difficult for students to understand since their necessity and effects emerge clearly in the large-scale or complicated design situation. For connecting both ends of this gap in design education, our approach enforces such iterations or cycles upon students. Thus, sessions are organized so as for students to design and produce devices twice. That is, it is required that after a device is designed and produced, another device is designed and produced with sharing its fundamental design concepts in the tight course schedule. Besides, the experiment of designed devices is a component of the project-based design course. There are two options on its position. The first is that redesign and reproduction is before experiment. The second is that redesign and reproduction is after experiment of the first set of designs. While the latter may be a straightforward position, the former might be a proper position for the design problem of large systems. At least, since there would be improvements even in production method or production schedule, or since the property of materials is revealed after the first production, the former must have another important meaning from the latter.

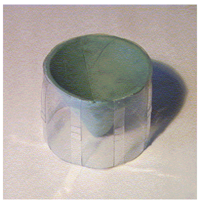
2.3 Analysis of synthesis

As Petroski pointed out [5], failures are the significant sources of engineering knowledge. While such causality is macroscopically evidential in the progress of engineering, design activity may include it in various forms and any degrees, off course in the above iterations and cycles. It might be effective for design education that students conscientiously visit their design process and design results immediately after their execution. Therefore, our approach put the sessions for analysis of design. To lead meaningful observation and discussion, student teams share the same subject and they compete the performance of designed devices. This brings various design concepts, alternatives and some types of consequent successes and failures under the same condition and in the classroom. For instance, it may be the case that different teams implement the same concept into their designs, but their performance are fairly different each other. Such a happening can be a superior source for leaning the meaning of a system, i.e., how a part affects the whole, what is the side effect of a part on the total performance, and so forth.

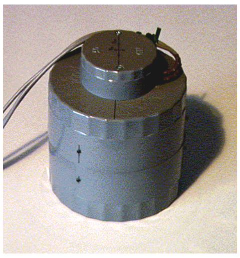
The above scenario on analysis of synthesis requires rich and shared records on how all student teams perform their activities. Thus, in our implementation of project-based design class, the results of every team's activities in every session are uploaded to the homepage of the class for sharing information and enabling to revisit their records in anytime of the schedule. Beyond the records on the design process, the physical phenomena of designed devices are more essential evidences on superior or inferior points of design concepts and their chain toward total performance. Thus, our approach combines scientific measurement in experiments of designed devices and provides students quantitative data, photos, and/or videos for enhancing students' analysis.

2.4 Materials of design subjects

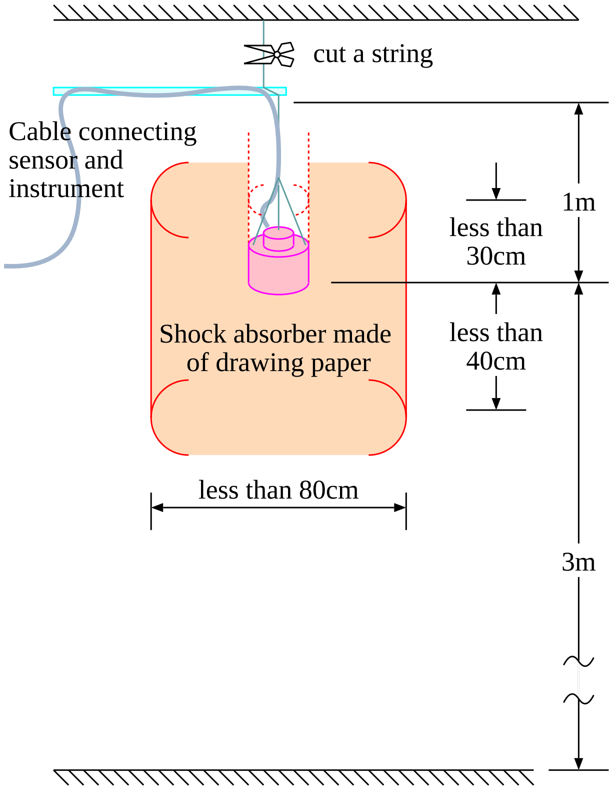
In summary, we configured a new style, in which planning, conceptual design, embodiment design, detail design, production, redesign, reproduction, design review, testing, and analysis of experiment results and executed design process are assigned step-by-step for each design team. When our department introduced such a project-based learning class for undergraduate third-year students, the duration of class is limited within two months, in which there are two sessions in a week, due to administrative issues on the established ongoing overall curriculum. Behind this reason, short and tight class schedule has some merits. At least, it is expected that fresh impression on their decisions and consequent happenings under a shorter cycle enhances analysis of synthesis. However, if any rich engineering context is sought under the viewpoint of the contents of individual knowledge, it cannot be avoided that a design subject tends to be complicated, knowledge-intensive, and time-consuming in both designing and producing. As aforementioned, our focus is on the process issues for systematizing them. Therefore, the materials used for producing a device are limited to drawing paper, which is often used in



(a) Clay cone wrapped in transparent sheet



(b) Plastic container for it, on the top of which a three-axis acceleration sensor is installed



(c) Design space and free-fall condition

Figure 1 Design regulation of a shock absorber and its fall experiment

elementary education, and stick-type paste, which is usually used on desk. This limitation saves, off course, the time for production. It increases the possibility of alternatives due to their flexibility in form, it ensures safety, and students are very familiar with their qualitative property.

The following describes two design subjects that we are developing as implementation of such a style of design education.

3 Design project of paper-made shock absorber

3.1 Regulation of the design project

The first design subject, which was initially introduced in 2001's fall, is to design a paper-made shock absorber for preventing deformation of a clay cone installed in a container under three meter free fall [6]. Figure 1 shows its regulation. Part (a) is a clay cone molded. Its diameter is 100mm, its height is 73mm, its shell thickness is 3.4mm, its base is empty, and its mass is 93g. Part (b) is the container, which is made of vinyl chloride by diverting piping components. The clay cone is wrapped with transparent sheets to prevent sticking it on the inner walls of a container at drop experiment as shown in Part (a). A three-axes acceleration sensor is equipped on the top of a container as shown in Part (b). Part (c) illustrates the regulations for designing an absorber. That is, the height of drop is 3.0m under free fall. Material of a shock absorber is limited to eight sheets of drawing paper, each size of which is 540mm $\times$ 380mm, and density of which is 151g/m^2, and stick-type paste. Geometry of a shock absorber must fit within a column of 80cm diameter and 70cm height. Three or four members of each team must finish production within three hours.

The above subject is arranged to be partially analogous to automobile crash safety design.

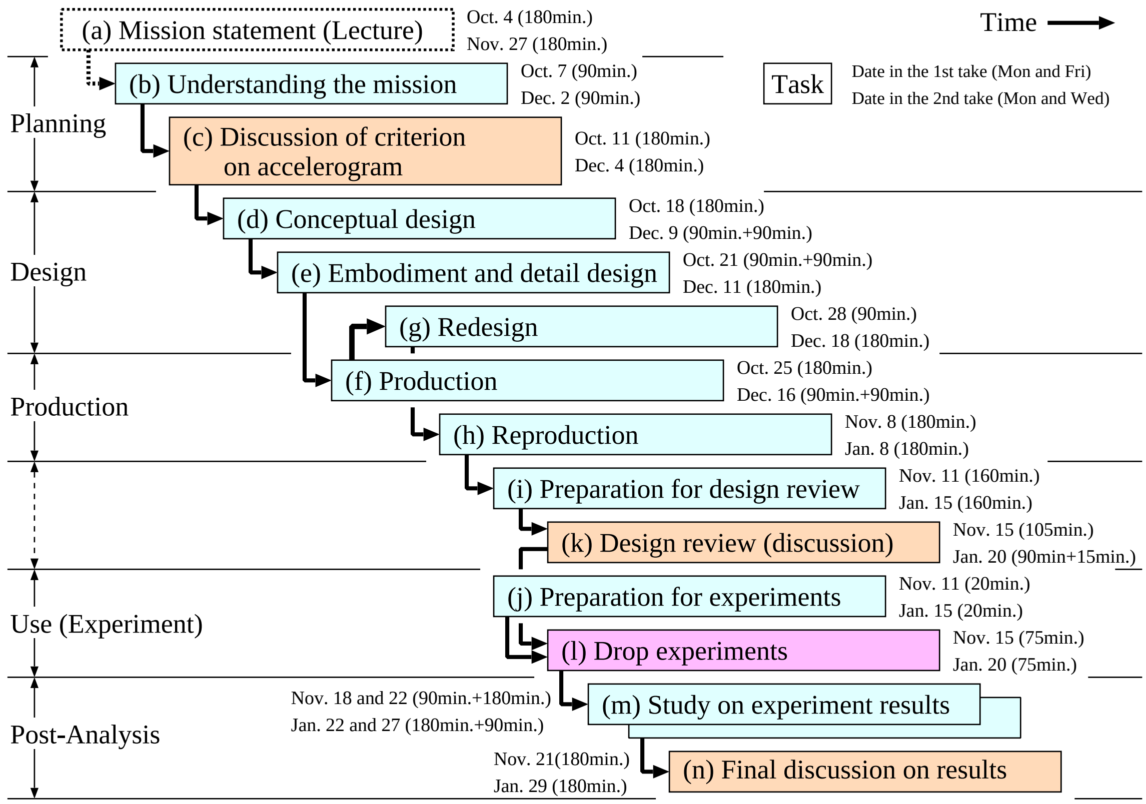
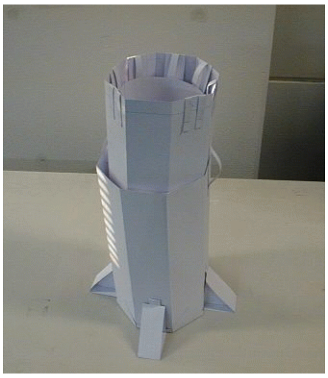


Figure 2 Timetable of a project course

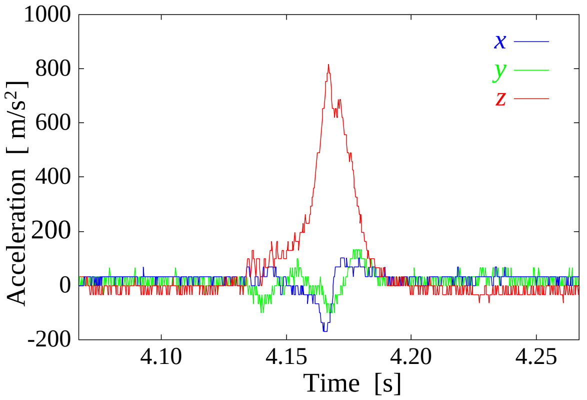
While it is not a real-world problem, it is multidisciplinary under mechanical engineering context and requires students' facing real applications of their knowledge learned in individual subjects such as dynamics of machinery, strength of materials, fluid mechanics. The hidden key point of this design problem is how to distribute limited resources, such as paper volume, fabrication time, among speed reduction, orientation control, direct shock absorption under an inspired design concept. For enhancing the possibility of reflective learning through analysis of synthesis, the scene of crash is videotaped by a high-speed digital video camera in addition to the measurement by a three-axes acceleration sensor equipped on the container.

3.2 Time schedule of a course

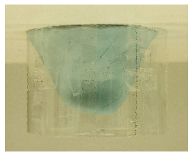
Figure 2 shows the concrete course schedules in 2002 academic year. The first session (a) is a lecture for explaining the class purpose, and the regulation of the subject, some hints for good designs. In the session (b), each student team defines a criterion for numerically grading performance of absorbers with accelerogram. In the session (c), all students discuss which is the best criterion. This session brings students clear understanding of the design problem in the early phase. The sessions (d), (e) and (f) is a sequence of conceptual design, embodiment and detail design, and production. The succeeding sessions (g) and (h) are its iteration for enhancing the chances toward act-reflect-change loops. This iteration in the very tight schedule is enabled by the small-scale design problem and ease in fabrication of papers as aforementioned. The session marked with (i) and (j) is for preparation of design review and molding clay cones. In the session marked with (k) and (l), all teams make presentation on designed results as design review, and then all absorbers are dropped for testing their performance. In the two sessions marked with (m), all teams independently investigate and discuss what happened in the last six weeks. In the final session (n), students present the results of such post-analysis by team and



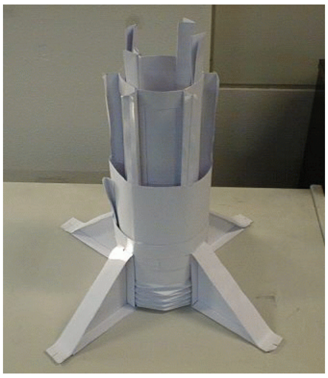
(a) Shock absorber of Team B



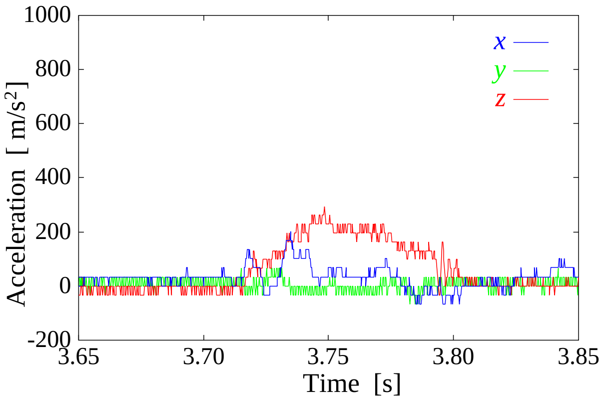
(b) Accelerogram of B drop



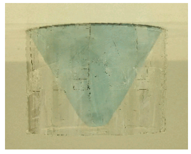
(c) Deformed clay cone of B drop



(d) Shock absorber of Team C



(e) Accelerogram of C drop



(f) Deformed clay cone of C drop

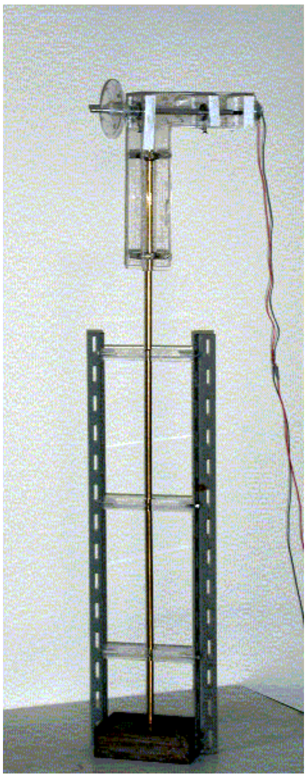
Figure 3 Examples of designed shock absorbers and their performance

discuss the design results and underlying meanings on the design process each other.

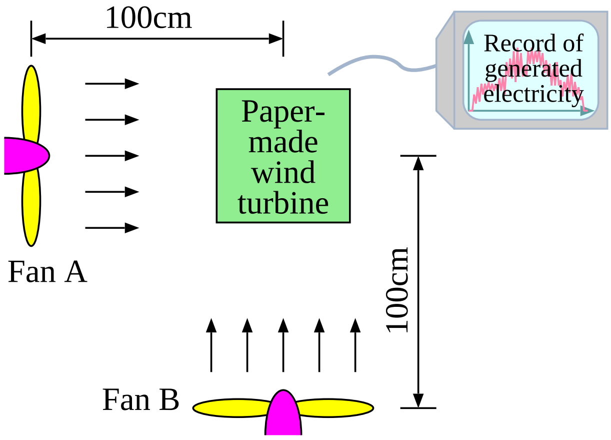
3.3 Examples of designed devices and their outcomes

In executing the above learning course, several interesting things are observed. For instance, although most students initially complained fuzziness on paper properties, etc., they became finally aware of the necessity of superior design decisions under fuzzy situation in the early phase of design process through this iteration. This point is justified by the fact that many students made somehow any comments on the fuzziness in the final presentation in the session (n). Since it is usually very difficult for young people to accept and work around the fuzziness, the framework of our approach must successfully implement an essential component for educating the tacit knowledge for systematizing individual knowledge on the contents. In addition, some teams drew graphs similar to morphological chart, design process flow chart, etc. as their own ideas. While these indicate the direct outcomes of this class, it was at least felt that it subsidiarily facilitates teaching engineering design in another lecture-style class.

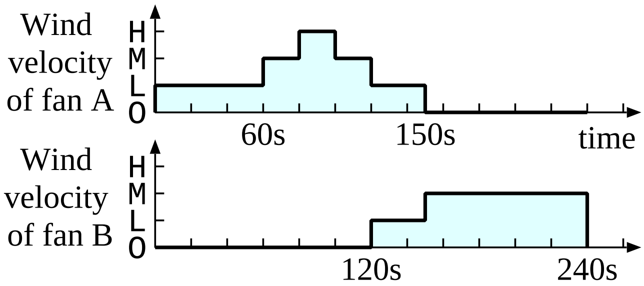
Regarding the performance of shock absorbers, some teams accomplished successful design and some teams did not. Some teams improved their design in redesign and reproduction and some teams did not. Figure 3 shows two designs in the second run of 2002 (the fourth run in total). Part (a), (b) and (c) show the shock absorber, accelerogram of drop test, and deformed clay cone of Team B, and Part (d), (e) and (f) show ones of Team C, respectively. While the outer shape of both is similarly a column and four staves are put on it for preventing



(a) The base for installation of a paper-made wind turbine



(b) Spatial arrangement of devices



(c) Time chart of wind direction and velocity

Figure 4 Design regulation of a wind turbine

turnover, the former has a mechanism that the container tears several sets of paper-made tendon belts in a stroke within the column piston. The latter installs two large paper-made air-bags in the column. As shown in accelerograms of Part (b) and (f), the initial response just after the shock is very similar. But the peak in the former is higher than one in the latter, and the duration absorbing the shock in the latter is longer than one in the former. These cause the difference of clay deformation, which is shown in Part (c) and (f). This indicates that scientific measurement is effective to lead students to deeper understanding not only the phenomena in drop experiment but also the tradeoffs or conflict among design concepts and alternatives. At least, it was ascertained that students concretely investigated causes-and-effects of design decisions and then they were approaching the image of paradigmatic meaning of engineering design by visiting real devices, videos and accelerograms of their drop experiments as intended.

4 Design project of paper-made wind turbine

4.1 Regulation of the design project

The second design subject, which was introduced in 2002's fall for expanding the number of students in addition to the above subject, is to design a paper-made wind turbine for power generation. The design of wind turbine has various design options such as lateral one or longitudinal one, the number of blades, shape and size of each blade, etc. as practical and real-scale ones are diverse. Figure 4 shows the regulation of the subject. Part (a) shows the base for installing a lateral-type wind turbine. For creating a situation similar to the first subject and meeting with time limitation, the shaft with a generator is commonly prepared beforehand, the subject is concentrated to designing configuration and geometry of a turbine and blades, directional control wing, etc. After each team produces a turbine on a 12cm compact disk plate and a directional control device, the former is installed on the disk with the same diameter at the tip and the latter is attached on the tail part with double-faced tape. The generator is a motor used for toys. The materials that can be used for production are limited to drawing paper and stick-type paste. The time permitted for production of a wind turbine is 120 minutes for a team of three students and 90 minutes for a team of four students.

Part (b) of Fig. 4 shows the arrangement of the above base and two electric fans. Part (c) shows the time schedule of switching their power. In the schedule, three different levels of airflow, which directly corresponds to the switching levels of the electric fan, are assigned. Fan A is on and B is off in the first half of the schedule, fan A is off and B is on the second half, and both fans A and B are on within thirty seconds between both phases. Thus, each team, for instance, is required to search the best attack angle of blades that compromise the optimal angles for respective airflow velocity. It is a case that a certain angle can be resistance under a range of airflow velocity, to take care for quick response against velocity change. Further each team must install directional control devices on the base enough to change its orientation by ninety degree at the change of airflow direction. In power generation test, performance of a wind turbine is recorded with generated power volume in a form of time history.

4.2 Time schedule of a course

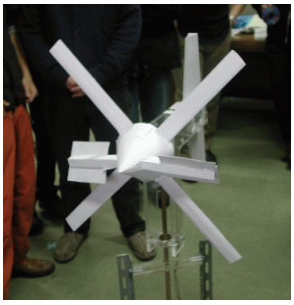
While the wind turbine subject is similar to the shock absorber subject, the different point exists on the availability of background theory. Regarding the shock absorber subject, its behavior is complicated and driven by a sequence of events. Thus, it is difficult to design it based on clear theories especially under a limited time. The major sources of design concepts tend to be expertise deduced from theories, analogy to existing devices, etc. On the other hand, the behavior of wind turbines is driven by a kind of equipoise among several power sources. Thus, some parts of mechanisms involved in it can be explained theoretically, and detail design changes can be deduced under articulated knowledge. It is also a major component of design education to being students an experience to utilize such theories under a real situation, which is combined with other fuzzy issues. In other words, this subject is expected to have a merit for teaching that effectiveness and limitation of a theory exist together in any real engineering problem.

By considering the above point, the course schedule shown in Fig. 2 is slightly modified for the wind turbine subject. The session for criterion discussion (c) is eliminated, because the criteria on wind turbine performance is natively clear as power generation. After the initial design and production, all devices are tested tentatively with recording only power generation volumes at all three levels of airflow without recording detail time history. This information is enough for checking static aspects of performance but insufficient for examining dynamic response of performance. Besides, it is permitted for each team to test devices at any time, although students need to spend time for producing them. Then, every team goes to the sessions of redesign and reproduction. Finally all students do post-analysis in a similar way to the shock absorber subject.

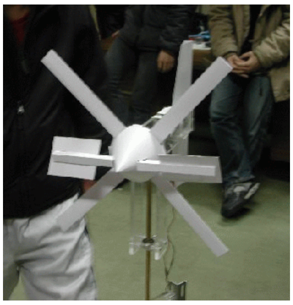
4.3 Examples of designed devices and their outcomes

Figure 5 shows two designs in the second run of 2002. One of Team H, shown in Part (a), is the best of the initially designed devices, and one of Team F, shown in Part (e), is the best of the redesigned devices.

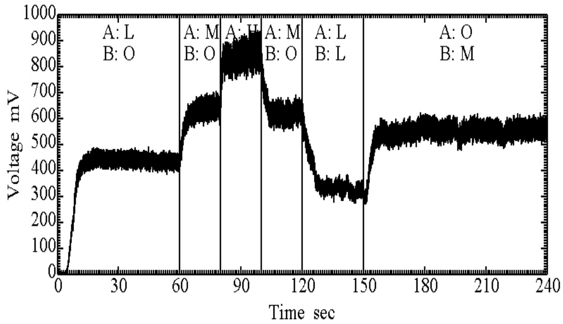
The device of Team H has six blades, among which two blades with large attack angle are in the front and four blades with small attack angle are in the rear. It is a trick that the front



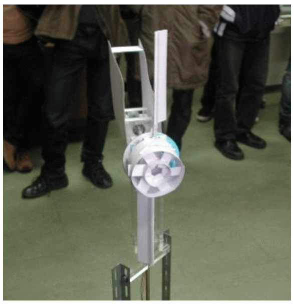
(a) First design of Team H



(b) Second design of Team H

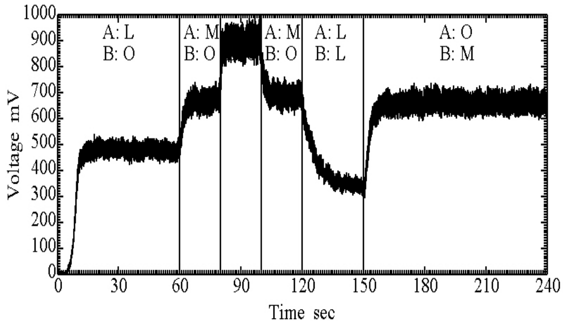


(c) Electricity generated by (b)



(d) First design of Team F

(e) Second design of Team F



(f) Electricity generated by (e)

Figure 5 Examples of designed wind turbines

two blades are thrown out under the high-speed rotation due to centrifugal force. That is, they generate motive power for starting rotation by large attack angle, but they are not effective under strong airflow. Thus, the rear four blades with small attack angle intend to mainly receive airflow once the device starts to rotate. Since the two blades can be resistance against such a circumstance, they must be thrown out. Regarding the initial design shown in Part (a) of Fig. 5, one of the front blades was thrown out under the initial low airflow, another was thrown out under the succeeding medium airflow, and the power generation level under the high airflow was 510 mV. Regarding its redesign, which is shown in Part (b), they tried to improve small details and production accuracy for improving its performance. As shown in Part (c), the front two blades were thrown out under the initial low airflow, and its performance become double, but one of the rear blades was also thrown out under the high airflow. The last accident is confirmed in Part (c) as the difference of power levels at the medium airflow zones by fan A and the airflow zone by fan B. Besides, it was confirmed that the device without the front blades could not start to rotate even under the strongest airflow due to too small attack angle.

The device of Team F consists of two subsystems as shown in Parts (d) and (e) of Fig. 5. The inner part is a set of small blades with large attack angle. The outer main part is two tapered torsional blades with small attack angle. The former is for generating starting force, and students thought that it is not the resistance against the latter because of small diameter. The form of the latter is aimed to well follow to the theory of fluid mechanics even under the property of paper. The performance of the initial design of Part (d) was 270 mV under the high airflow, which was the sixth place among eight teams. Reflecting such a result, Team F accomplished some significant refinements. The angle of inner blades is made to be large, the number of inner blades was increased, and their diameter was increased to almost fit with the compact disk plate. The sectional form of its directional control wing was changed to be triangle for quick response on airflow change. The integration of these improvements brought the power generation history shown in Part (f) which was the first place.

As demonstrated with the above two cases, the paper-made wind turbine subject brought students various outcomes similar to but slightly different to ones that the paper-made shock absorber subject brought. At least, students reported the importance of total balance, teamwork, comparison of many alternatives, integration of theories and experiments, prototyping, etc. toward superior design in the final discussion session.

5 Concluding Remarks

This paper configured a framework of project-based design education with the emphasis on the tacit knowledge for systematizing individual knowledge over a specific artifact. While the framework adds some new definitions onto project-based design education with reflective learning through analysis of synthesis, it is more difficult to judge how its educational objective is accomplished than one of conventional design projects. Its true outcomes will be emerged through coevolution with other preceding and succeeding subjects. In other words, it is expected that the described style of design projects guides students toward deeper understanding of other subjects by changing their attitude on engineering knowledge. Thus revolution of design education with reflective learning follows total design of engineering curriculum, and the outcomes might be measured under the total integration.

Acknowledgements

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