An Engineering Education toward Sustainable Society through Manufacturing a Flying Toy "Taketombo"*

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Abstract

In order to establish a sustainable society, a fundamental concept of industrial product design is to reduce as far as possible the use of starting resource materials. For education with respect to the design and manufacture of products, it is necessary to consider the environmental impact of materials selection. In the present study, we focus on bamboo as a design material because it has a wide habitat, grows rapidly, is carbon neutral, and can be consecutively deforested. In order to evaluate a practical educational approach, we examined the taketombo, which is a popular traditional Japanese flying toy made from bamboo, with respect to basic areas of mechanical engineering. In the present paper, practical design education is described based on the taketombo. By adopting this teaching material for design education, students who were not stimulated by traditional educational equipment, such as a Gettingen-type wind tunnel, became interested in our launch pad. Through this product design exercise, which incorporates responsible consideration for the environment in addition to ecological concepts, students were educated through design experience of the taketombo.

Key words: Bamboo, Taketombo, PBL, Engineering Education, Physical Computing

1. Introduction

In industrial commodity design for a sustainable society, it is desirable to achieve the necessary functions using fewer parts and materials. Moreover, reusability and recycling must be taken into consideration.

Numeric simulation is often used in such design in order to reduce the costs associated with prototype manufacture. However, young engineers with little experience will often mistakenly assume that the actual physical prototype will exhibit exactly the same behavior and characteristics as the simulated object. Moreover, when it is necessary to consider a range of different materials, the constitutive equations are often insufficient, and assumptions must be included in the simulations, which do not always conform to actual reality. For this reason, simulations are limited in their ability to completely describe the characteristics of physical objects. Consequently, when training young engineers, problem-based learning (PBL) methods are important for maintaining links between theory, simulations and reality.

Through the concept of the three R’s (reduce, reuse, recycle), a young engineer can be made conscious of environmental factors such as choosing materials whose production does not require high energy costs. However, in practical PBL situations, the environmental
conformity of materials is often ignored since there are restrictions with regard to safety, cost, and time available. For example, when using an experimental wind tunnel, wing or automobile models fabricated from metal or resin are often provided by the instructor. Therefore, it is rare for a student to consider the environmental suitability of a given material, because of the blind use of the material provided by the teacher. However, when a skillful engineer begins a design, material selection is one of the highest priorities. For this reason, education in materials selection is important in order to provide students with an understanding of sustainability concepts. In addition, if the choice of material is appropriate, prototypes can be easily created and the desired test results achieved.

From the viewpoint of processing and safety, paper and styrene foam are more suitable than metal or resin. However, material strength and rigidity must also be taken into consideration, as should the impact on the environment. One well-known environmentally friendly material is kenaf, which is cultivated in several places around the world, including south-east Asia. In recent years, Hall et al.[1] reported the manufacture of a wheelchair using kenaf, and for educational purposes, Ogawa et al.[2] produced windmill blades from kenaf.

Bamboo is also an ecologically friendly material. It grows over a wide area of Asia, does not have an adverse influence on other plants, does not wither land, and exhibits rapid growth. Moreover, when used as a composite material, bamboo has far greater rigidity than kenaf. Therefore, bamboo is often used as a structural material.

In the present study, we consider the design of a taketombo, which is a traditional Japanese toy. Designing a taketombo requires an understanding of basic dynamic effects (centrifugal force, etc.), hydrodynamic effects (drag and lift, etc.), material-mechanics considerations (material modification and destruction, etc.) and the relationship among these factors. Moreover, since the rotational energy generated by the moment of inertia of the taketombo at the time of launch is converted into potential energy as the taketombo rises, mechanical-dynamics factors must also be considered. In the design and construction of the launch pad for the taketombo, a knowledge of control engineering, which is an important aspect of machine education, is also required.

Thus, the taketombo incorporates a number of elements that constitute the foundation of mechanical engineering[3]. Moreover, the taketombo is easy to manufacture and can be flight tested in a relatively confined area. In addition, its performance characteristics are easily determined. The present paper describes the importance of the choice of material in a realistic engineering design educational program (such as PBL), using taketombo design as an example. Environmental issues are also emphasized, with a view towards maintaining a sustainable society.

2. Design Education

Akioka[4] published the results of a study on the design of a “super-taketombo”, and Azuma[5], who is famous in the field of flight dynamics in Japan, also carried out research on taketombo design. In these studies, the primary goal was to obtain a basic understanding of the phenomenon involved rather than developing practical design techniques. In almost all cases, design techniques based on empirical rules were used. Consequently, taketombo makers will generally employ designs based on past precedents rather than giving deep consideration to the design process.

In the design of a taketombo, many problems can occur such as reduced flight performance due to poor processing accuracy and frequent breakage upon landing. In designing an efficient taketombo, the first goal is to acquire and process the material. For this purpose, bamboo becomes an obvious choice because of its material characteristics and environmental friendliness.
2.1. Characteristics of bamboo

In the present study, bamboo is used as the building material. Bamboo’s excellent rigidity makes it a suitable design material as well as a structural material. For example, bamboo is used for fishing rods and umbrellas, and in Japan is sometimes used as a replacement for iron frames in bridges.

2.2. Acquisition of bamboo material

Bamboo may be acquired by recycling moso bamboo discarded at the time of demolition of rafts used in oyster cultivation (Fig. 1). Bamboo that has been soaked in salt water for an extended period is insect resistant, and a smoking process is not necessary as is the case with freshly cut bamboo. After recovery, the bamboo scrap is cut by a rotation saw to form rectangular slices. It can also be cut into strips using a special hatchet for working bamboo.

In the present study, the students learning engineering design based on a taketombo used scrap bamboo from rafts, old bamboo rulers which have become deformed and bamboo sold in home centers. In addition, the shaft of the taketombo was made from a recycled bamboo skewer that is normally used for cooking.

![Fig. 1: Scrap bamboo from rafts used in oyster cultivation](image)

2.3. Design manual

First, the students were told that the taketombo should be designed so as to achieve maximum altitude.

2.3.1. Conservation of energy

We provided the following instructions to the students. The driving force of the taketombo is an inertial force which depends on the initial rotation velocity. Moreover, if \( I \) is the moment of inertia, then prior to launch, the taketombo has a rotational energy \( E = \frac{1}{2}I\omega^2 \), where \( \omega \) is the angular velocity. Next, the flight of the taketombo was explained from the viewpoint of conservation of energy, as follows. The flight of the taketombo begins upon its release from the hand. The taketombo rises by changing kinetic energy into potential energy, as shown in Fig. 2. The potential energy is a maximum at the maximum altitude. At this time, if \( \omega = 0 \), then the rotational energy has completely changed into potential energy, and the student must consider the efficiency of the energy transfer mechanism involved.
Fig. 2: Energy of the *taketombo* during flight

Fig. 3: Coordinate system

Fig. 4: Variation of angle of attack
2.3.2. Aerodynamics

Since the drag effect for a *taketombo* is small, the inductive energy loss cannot be expressed as a valuation function. For design of a propeller that operated at a low Reynolds number (Re), Harada[6] used the propulsion efficiency as the valuation function. In the present study, we use the energy conversion efficiency, describing the transformation of rotational energy into potential energy, as the valuation function, and simplify it further in order to make it intelligible for educational purposes. The coordinate system used is shown in Fig. 3.

Since the bamboo is in the form of strips, we herein consider a two-blade *taketombo*, which can be easily operated by anybody by simply twisting the handle. For a *taketombo* rotating at an angular velocity $\omega$ [rad/s], the speed $v$ of the air at a distance $y = y_0$ from the $x$-axis is denoted as $y_0\omega$.

Since Re can be determined based on the ascending vertical angle $\alpha$ and the wing length $L$, the lift and drag become roughly computable. When $\omega$ and the rate of climb (vertical velocity) change, the inlet velocity also changes. So, Re and $\alpha$ are continuously changing during flight.

We used a flat plate aerofoil in order to simplify the explanation of the phenomena involved and to make the calculations more easy. As can be seen in Fig. 5, where AR is the aspect ratio of the wing (the ratio of its length to its breadth), the computational fluid dynamics (CFD) results[7] for the drag and lift coefficients with AR=$\infty$ (ideal wings of infinite length), are not easy to obtain experimentally, for example in a wind tunnel[8]. The correctness of the CFD results can be assessed by comparing them to the experimental data, so that the theoretical and experimental approaches compliment each other. In this way, students come to understand that although CFD is useful, it is not perfect.

![Characteristics of a flat plate aerofoil](image-url)
2.3.3. Material mechanics

Like many industrial devices, aerodynamic and structural characteristics must be taken into consideration when designing the taketombo. The physical properties can be easily obtained because bamboo is commonly used as a building material[9]. An example of a design based on these physical properties is shown in Fig. 6. The problem set for the students is a study of the tensile stress resulting from the centrifugal force in a taketombo. Using a simplified formula such as that shown in Eq. (1), the student can carry out a desk study on this topic.

\[
\delta_{(y=R_w)} = \frac{F}{S} = \int \frac{df}{S_0} = \int_{y=R_0}^{y=R_w} y\omega^2 dm/S_0 \quad \cdots (1)
\]

Fig. 6: Schematic diagram of centrifugal stress

Fig. 7: Stress distribution during lift

In addition, the lift computed from Figs. 4 and 5 can be used to conduct a Finite Element Analysis (FEA) of a static taketombo with regard to the stress distribution during lift. An example of the results is shown in Fig. 7. Thus, the students are made to study the force which is calculated drag and lift coefficients obtained from hydrodynamics data (Fig. 5). Designing a taketombo is therefore considered to be a suitable calculation and design problem.

2.4. Flight quality assessment for a taketombo

2.4.1. Tire drive type launcher

In order to efficiently investigate the flight performance of a taketombo, a launch device that mimicked the rotation (Fig. 8) of the shaft by hand was manufactured.

The shaft of the taketombo is fixed by two (or three) sets of three tires, which apply a driving force to increase the rotational velocity. The moment the velocity reaches a set value, the tires separate from the shaft of the taketombo. Fig. 9 shows a photograph of the manufactured launch device. We used gainer-mini, which is a physical computing board commonly used with arduino[10] in Japan, to control the three rotary motors of the launch device. The control program was written in Processing, which is an open source programming language[11], and the rotation and release time of the taketombo were controlled (Fig. 10).
2.4.2. Altitude measurement

The altitude achieved by the *taketombo* was determined trigonomically based on video photography, as shown in Fig. 11. The altitude is determined as follows:

\[
h = a + (D - L) \tan \theta_1 - c = b + L \tan \theta_2 - c \tag{2}
\]

\[
L = (a - b + D \cdot \tan \theta_1) / (\tan \theta_1 + \tan \theta_2)
\]
3. Practical Application of Design Education

We simplified the mechanical parts design loop for engineering products, and sample results are shown in Fig. 12. The main loop consist of 4 steps: (1) a designer works out a detailed plan for a product; (2) a prototype is created based on the proposed concept; (3) performance tests are carried out on the prototype; (4) If the test results are satisfactory, then the loop is completed. Otherwise, the process returns to step (1). In addition, CAE (Computer Aided Engineering) can be an effective means of reducing the number of prototype trials.

![Design process](image)

3.1. System manufacture

The design plans, such as the use of a flat plate airfoil, were explained to the students. Two types of taketombo were considered: a taketombo having a wing with a uniform cross section, which has existed for many years as an article of folkcraft (Fig. 13(a)), and the super-taketombo, which was proposed by Akioka (Fig. 13(b)).

The purpose of this education is for the students to design a super-taketombo using the technical capabilities they have acquired and the imagination to achieve their goal.

![Handmade taketombo](image)
The manufacturing process was designed to be completed in five steps based on the progress and degree of comprehension of the students.

STEP 1 (conceptual introduction): The students are asked to use a knife to manually produce a *taketombo* having a wing with a uniform cross section (Fig. 13(a)), without any special knowledge of mechanical engineering.

STEP 2 (basic theoretical introduction): The students attend lectures on mechanical dynamics, material mechanics, and fluid dynamics.

STEP 3 (design case presentation): The students examine the design of a super-*taketombo* (Fig. 13(b)), and then attempt to construct it using a knife.

STEP 4 (tool introduction): In addition to the manual use of a knife in STEP 3, the students can also carry out 3D-CAD and CNC (Computerized Numerical Control) machining. They can also use fundamental CAE methods such as FEM in 3D-CAD.

STEP 5 (application development): The students can use highly advanced FEM and CFD techniques, although specialized knowledge is needed to use CFD and calculation costs are very high.

These steps are carried out under the following schedule. STEP 1 consists of 90-minute exercises four times per month, and is a compulsory subject for freshman. STEP 2 consists of 90-minute lectures and exercises five times per term, and is an elective subject for third-year students. STEP 3 and STEP 4 consist of five 90-minute lectures and exercises taken as part of a graduate study program. STEP 5 is designed to be an advanced program for highly motivated students.

The total number of participants in STEP 1, STEP 2, STEP 3 and STEP 4 was about 100 for the six-year period from 2007 to 2012, 30 for the four-year period from 2009 to 2012, 20 for the three-year period from 2010-2012, and 10 for the three-year period from 2010-2012. As of 2012, no students have reached STEP 5 by themselves.

![Filing by hand](a)  
![Finished taketombo produced by hand](b)  

**Fig. 14: Example of STEP 2**

### 3.2. Example of design and manufacture

An example of STEP 2 is shown in Fig. 14. At this stage, many students simply copied the model and learned little. Examples of designs produced in STEP 4 are shown in Fig. 15. In this step, although students who do not make original designs, but instead imitate existing *taketombos*, do not fail, they also do not gain good experience. On the other hand, students who challenge themselves experience many failures and in this way achieve progress. A design example in which centrifugal force was not taken into consideration, resulting in fracture, is shown in Fig. 16. However, in many cases, the performance was improved through trial-and-error, as indicated in Table 1.
3.3. Flight experiment

The maximum altitude achieved by each taketombo was measured. The launching device shown in Fig. 9 was built and used for altimetry (Fig. 11). Fig. 17 shows the experiment being conducted. Attempts to control the angular velocity to be the same while using the same taketombo indicated a reproducibility error of less than 8%. A part of the record of an undergraduate student who progressed to STEP 4 is shown Table 1. Students
are often not interested in wind tunnel tests, in which the object of study is fixed. However, the students expressed a great deal of interest in the newly designed taketombo launch device.

4. Conclusion

In order to achieve a sustainable society, the training of next-generation engineers is extremely important. In the present study, three-dimensional CAD, which enables the use of numerical computation methods such as FEM, including the element of a dynamics system subject, was used. It is necessary for students to understand the differences between reality and simulations, and the design and manufacture of the taketombo described in this paper is a useful way to teach this.

The students managed to design lighter and stronger products than conventional ones. Furthermore, students who are not stimulated by conventional CAD lectures or wind tunnel experiments may find such an educational approach interesting.

In particular, when carrying out design education such as PBL, it was shown that a taketombo manufacturing theme was an effective means of education for a sustainable society.

References

10) Arduino: http://www.arduino.cc/
11) Processing: http://processing.org/